GE Advanced Liquid Metal Reactor

S-PRISM

by

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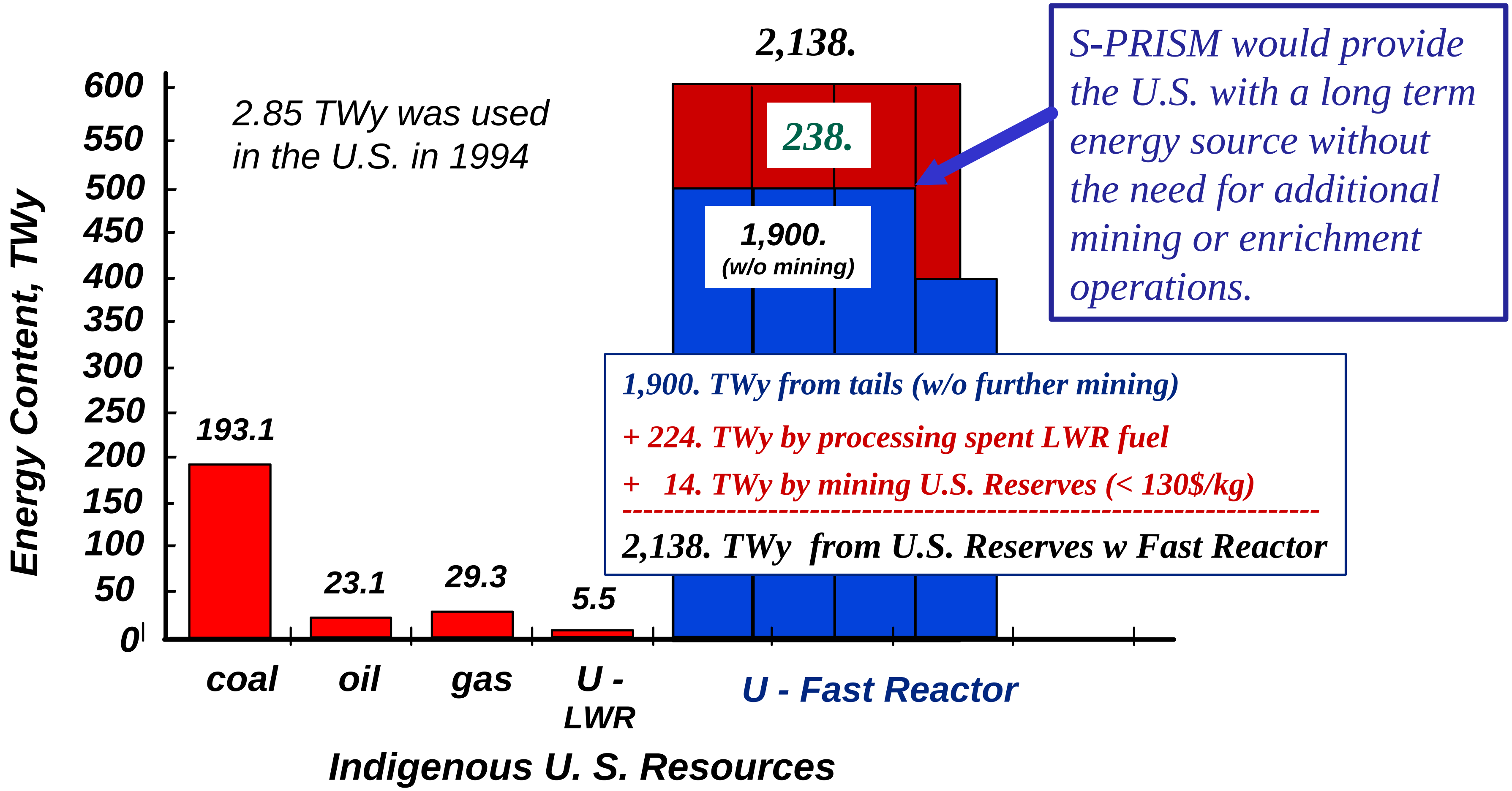
Topics

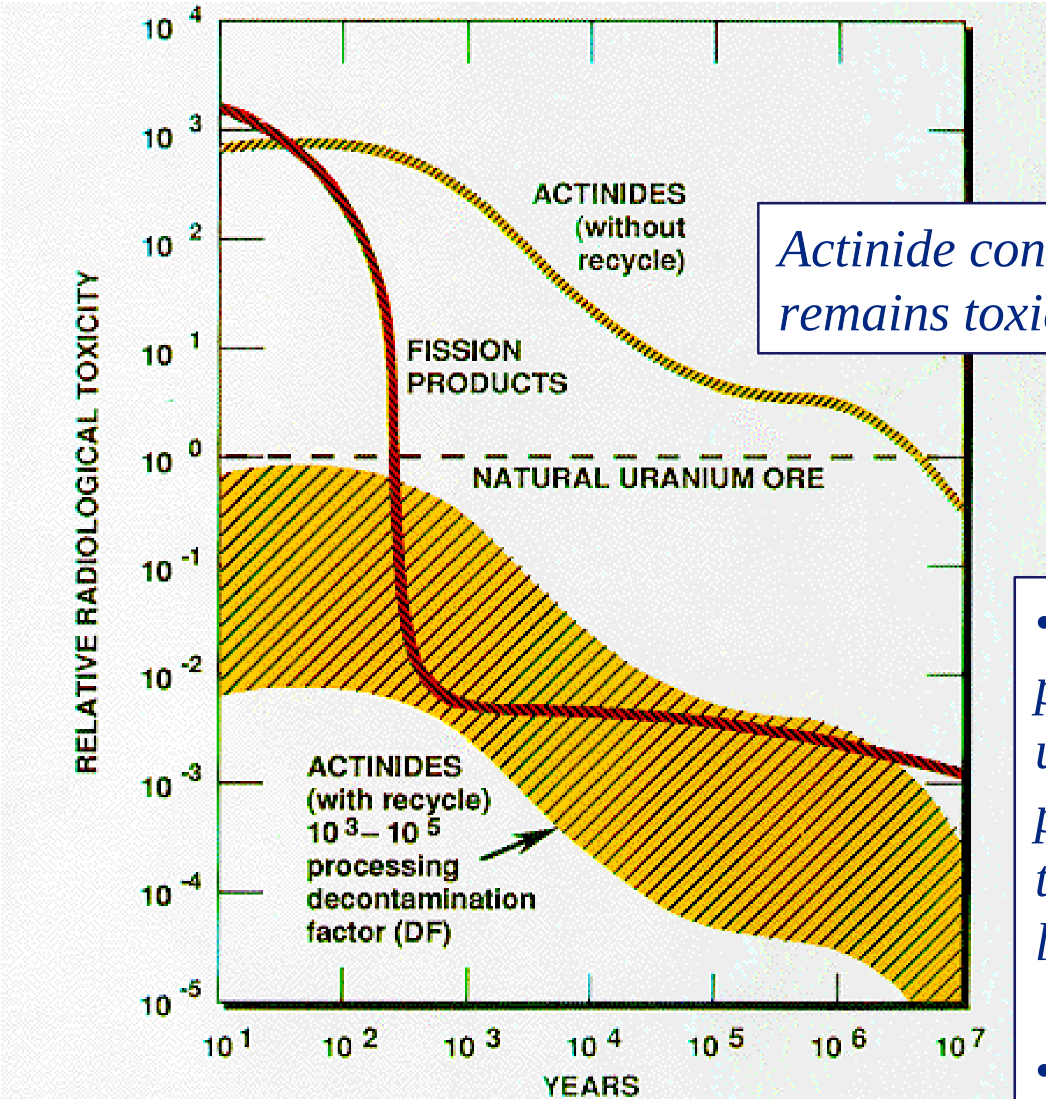
- *Incentive for developing S-PRISM*
- *Design and safety approach*
- *Design description and competitive potential*
- *Previous Licensing interactions*
- *Planned approach to Licensing S-PRISM*
- *What, if any, additional initiatives are needed?*

United States Energy Resources



Energy estimates for fossil fuels are based on "International Energy Outlook 1995", DOE/EIA-0484(95). The amount of depleted uranium in the US includes existing stockpile and that expected to result from enrichment of uranium to fuel existing LWRs operated over their 40-y design life. The amount of uranium available for LWR/Once Through is assumed to be the reasonably assured resource less than $130/kg in the US taken from the uranium "Red Book".

Time Phased Relative Waste Toxicity (LWR Spent Fuel)



Actinide containing LWR spent fuel remains toxic for millions of years

- *Processing to remove the fission products (~3% of LWR spent fuel), uranium (95%), and transuranics prior to disposal shortens the period that the "waste" remains toxic to less than 500 years.*
- *The recovered U and TRU would then be used as fuel and burned.*

Relative Decay Heat Loads of LWR and LMR Spent Fuel

Decay Heat Load	Decay Heat (Watts per kg HM)	
	LWR	S-PRISM
Spent Fuel at Discharge	2.3	11.8
Normal Process Product After Processing Spent Fuel • Pu from PUREX Process for LWR • Pu + Actinides from PYRO Process	9.62	25.31
Weapons Grade Pu-239	1.93	

During all stages in the S-PRISM fuel cycle the fissile material is in a highly radioactive state that always exceeds the "LWR spent fuel standard".

Diversions would be extremely difficult.

Co-Located Fuel Cycle Facility

Stage of the Fuel Cycle	Material Barriers: Isotopic	Radiological	Chemical	Mass and Bulk	Detectability	Technical Barriers: Facility Unattractiveness	Facility Access	Available Mass	Diversion, Detectability	Skills, Knowledge, Expertise	Time
Phase 1: Fresh fuel fabrication											
Mining											
Milling			Not required					Not required			
Conversion											
Uranium enrichment											
Plutonium storage											
Transport								Not required			
Fuel fabrication			Not required								
Storage											
Transport											
Phase 2: Initial core loading											
Storage of fresh fuel											
Fuel handling			Not required					Not required			
Reactor irradiation											
Phase 3: Equilibrium Operations											
Fuel handling				L			VL	I		M	L
Spent fuel storage				L			M	I		M	L
Head-end processing				M			VL	I		I	L
Fuel processing	VL	VL	L	M	VL	VL	VL	I	VL	I	L
Fuel fabrication				L			VL	I		I	L
Reactor operations				L			VL	I		M	L
Waste conditioning				L			VL	VL		I	VL
Waste shipment				VL			VL	VL		I	VL

Phase I
These opportunities for proliferation are not required for S-PRISM.

Phase 2
All operations are performed within heavily shielded enclosures or hot cells at the S-PRISM site.

Phase 3
All operations are performed within heavily shielded and inerted hot cells at the co-located S-PRISM/IFR site.

Key Non-Proliferation Attributes of S-PRISM

1.) The ability to create S-PRISM startup cores by processing spent LWR fuel at co-located Spent Fuel Recycle Facilities eliminates opportunity for diversion within:

- *Phase I (mining, milling, conversion, and uranium enrichment phases) since these processes are not required.*

and

- *Phase II and III (on-site remote processing of highly radioactive spent LWR and LMR fuel eliminates the transportation vulnerabilities associated with the shipment of Pu)*

2.) The fissile material is always in an intensely radioactive form. It is difficult to modify a heavily shielded facility designed for remote operation in an inert atmosphere without detection.

3.) The co-located molten salt electro-refining system removes the uranium, Pu, and the minor actinides from the waste stream thereby avoiding the creation of a uranium/Pu mine at the repository.

Incentive for Developing S-PRISM

- *Supports geological repository program:*
  - *deployment of one new S-PRISM plant per year for 30 years would eliminate the 86,000 metric tons of spent LWR fuel that will be discharged by the present fleet of LWRs during their operating life.*
  - *reduces required repository volume by a factor of four to fifty*
  - *All spent fuel processing and waste conditioning operations would be paid for through the sale of electricity.*
  - *limits interim storage to 30 years*
- *Reduces environmental and diversion risks*
  - *repository mission reduced from >> 10,000 to <500 years*
  - *facilitates long term CO_2 reduction*
  - *resource conservation (fossil <u>and</u> uranium)*
  - *allows Pu production and utilization to be balanced*
  - *utilizes a highly diversion resistant reprocessing technology*

Topics

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- *Design description and competitive potential*
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- *What, if any, additional initiatives are needed?*

S-PRISM Safety Approach

Exploits Natural Phenomena and Intrinsic Characteristics

- *Low system pressure*
- *Large heat capacity*
- *Natural circulation*
- *Negative temperature coefficients of reactivity*

Key Features of S-PRISM

- Compact pool-type reactor modules sized for factory fabrication and an affordable full-scale prototype test for design certification

- Passive shutdown heat removal

- Passive accommodation of ATWS events

- Passive post-accident containment cooling

- Nuclear safety-related envelope limited to the nuclear steam supply system located in the reactor building

- Horizontal seismic isolation of the complete NSSS

- Accommodation of postulated severe accidents such that a a formal public evacuation plan is not required

- Can achieve conversion ratios less than or greater than one

S-PRISM Design Approach

Simple Conservative Design

- *Passive decay heat removal*
- *Passive accommodation of ATWS Events*
- *Automated safety grade actions are limited to:*
  - *containment isolation*
  - *reactor scram*
  - *steam side isolation and blow-down*

Operation and Maintenance

- *Safety grade envelope confined to NSSS*
- *Simple compact primary system boundary*
- *Low personnel radiation exposure levels*

Capital and Investment Risk Reduction

- *Conservative low temperature Design*
- *Modular construction and seismic isolation*
- *Factory fabrication of components and facility modules*
- *Modularity reduces the need for spinning reserve*
- *Certification via prototype testing of a single 380 MWe module*

S-PRISM Features Contribute to:

- *Simplicity of Operation*
- *Reliability*
- *Maintainability*
- *Reduced Risk of Investment Loss*
- *Low Cost Commercialization Path*

S-PRISM Design Approach *(continued)*

1. Design basis events (DBEs)

- *Equipment and structures design and life basis*
- *Bounding events that end with a reactor scram*
- *Example, all rod run out to a reactor scram*

2. Accommodated anticipated transients without scram (A-ATWS)

- *In prior reactors, highest probability events that led to boiling and Hypothetical Core Disassembly Accidents were ATWS events*
- *In S-PRISM, ATWS events are passively accommodated within ASME Level D damage limits, without boiling*
- *Loss of primary flow without scram (ULOF)*
- *Loss of heat sink without scram (ULOHS)*
- *Loss of flow and heat sink without scram (ULOF/LOHS)*
- *All control rods run out to rod stops without scram (UTOP)*
- *Safe shutdown earthquake without scram (USSE)*

3. Residual risk events

- *Very low probability events not normally used in design*
- *In S-PRISM, residual events are used to assess performance margins*

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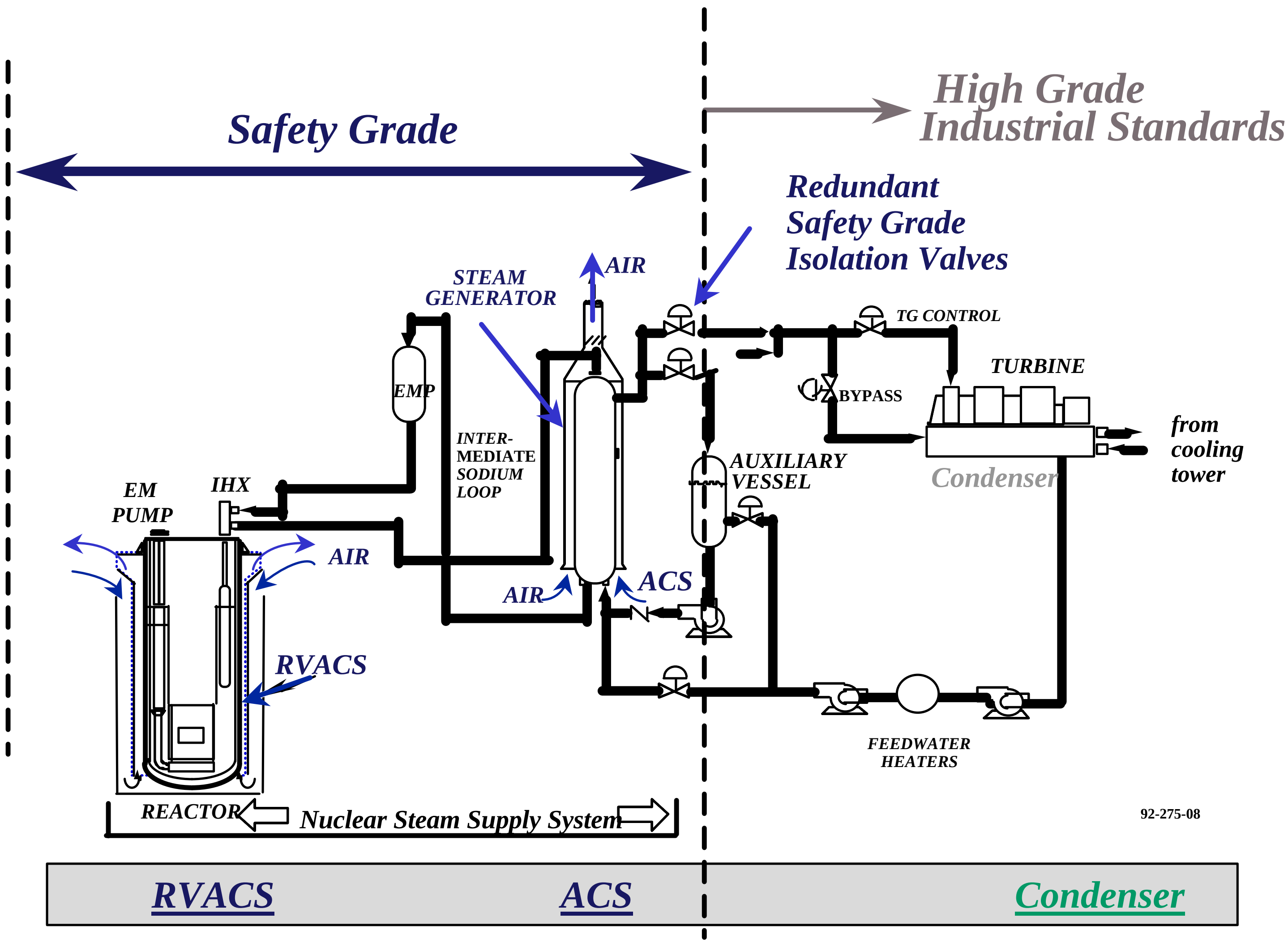
Power Train

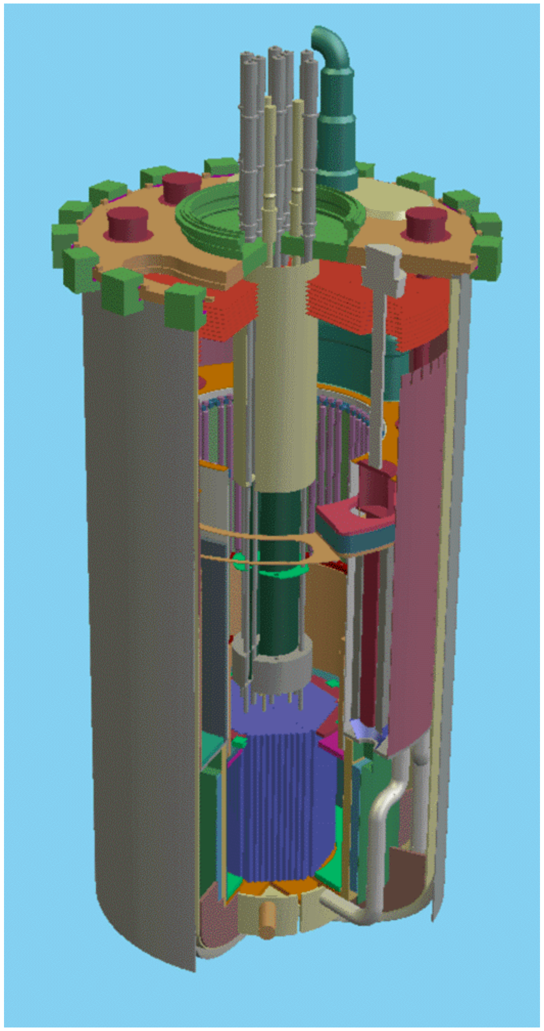


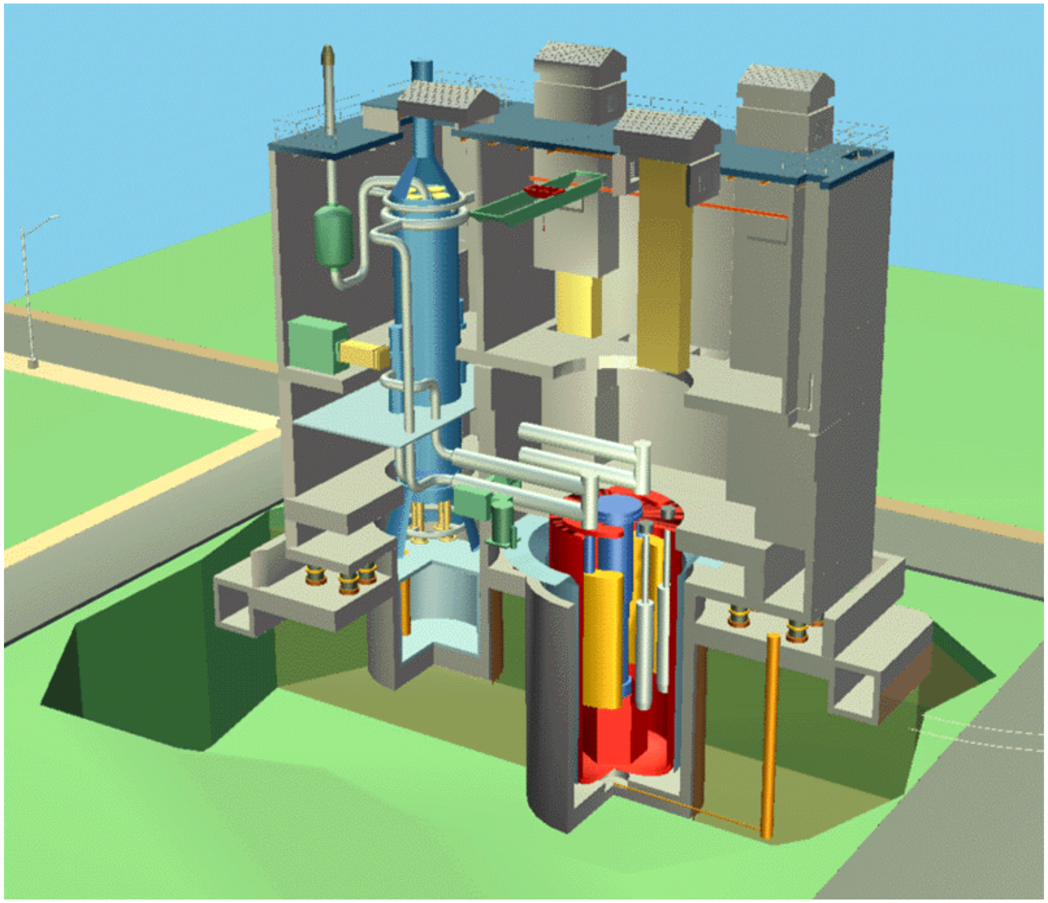
Shutdown Heat Removal Systems

S-PRISM - Principal Design Parameters

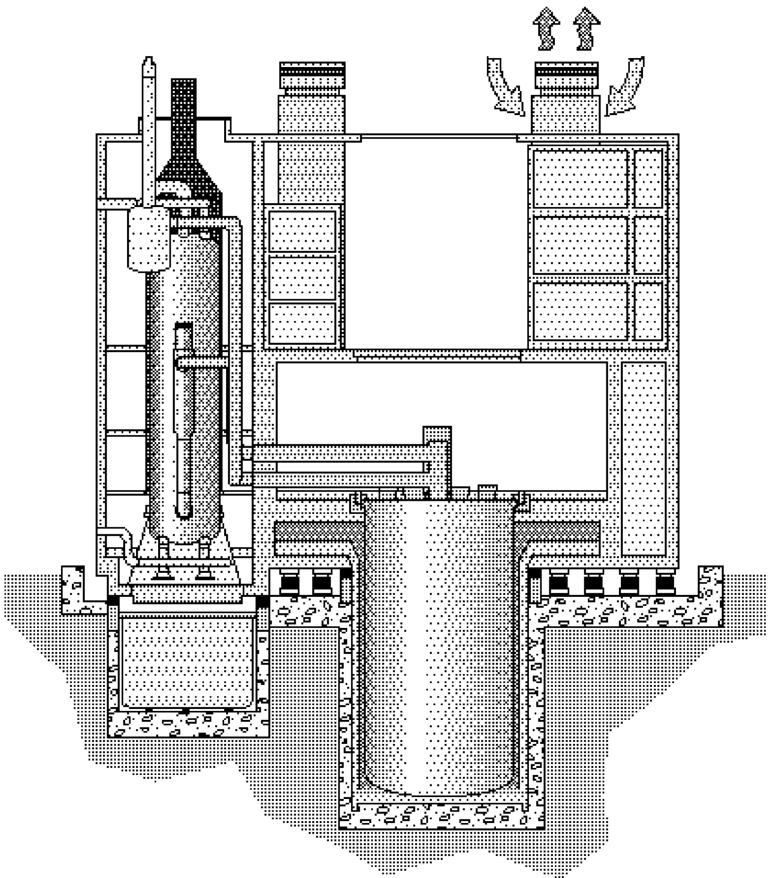
Reactor Module	
- Core Thermal Power, MWt	1,000
- Primary Inlet/Outlet Temp., C	363/510
- Secondary Inlet/Outlet Temp., C	321/496
Power Block	
- Number of Reactors Modules	2
- Gross/Net Electrical, MWe	825/760
- Type of Steam Generator	Helical Coil
- Turbine Type	TC-4F 3600 rpm
- Throttle Conditions, atg/C	171/468
- Feedwater Temperature, C	215
Overall Plant	
- Gross/Net Electrical, MWe	2475/2280
- Gross/Net Cycle Efficiency, %	41.2/38.0
- Number of Power Blocks	3
- Plant Availability, %	93

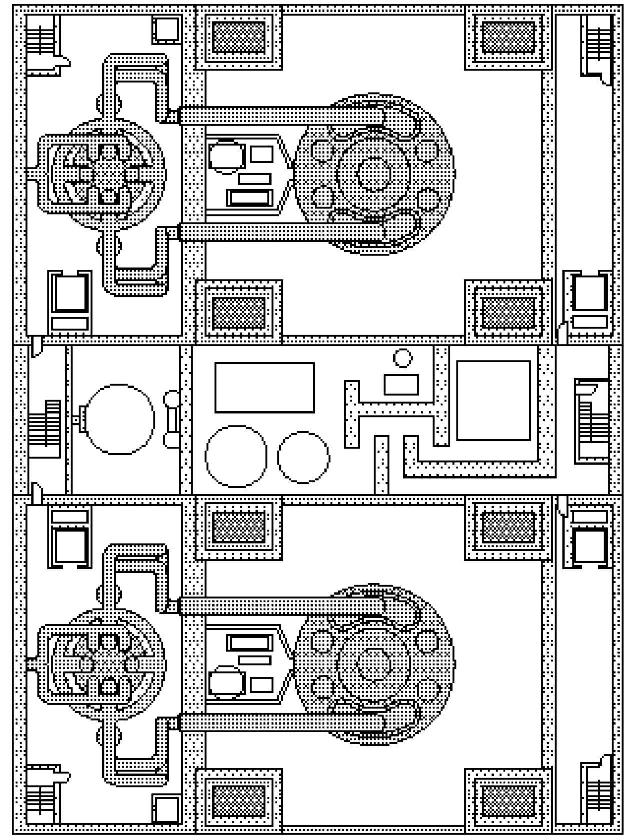
Super PRISM





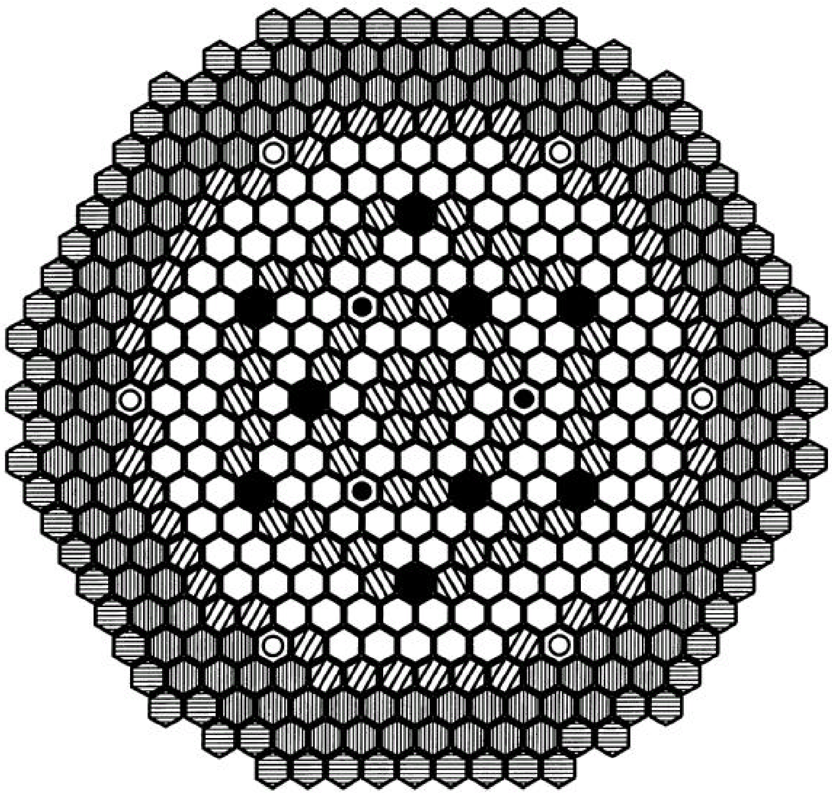
S-PRISM Power Block (760 MWe net)





Two 380 MWe NSSS per Power Block

Metal Core Layout



Number of Assemblies

Driver Fuel	138
Internal Blanket	49
Radial Blanket	48
Primary Control	9
Secondary Control	3
Gas Expansion Module	6
Reflector	126
Shield	72
Total	451

Fuel: 23 month x 3 cycles

Blkt: 23 month x 4 cycles

Oxide vs. Metal Fuel

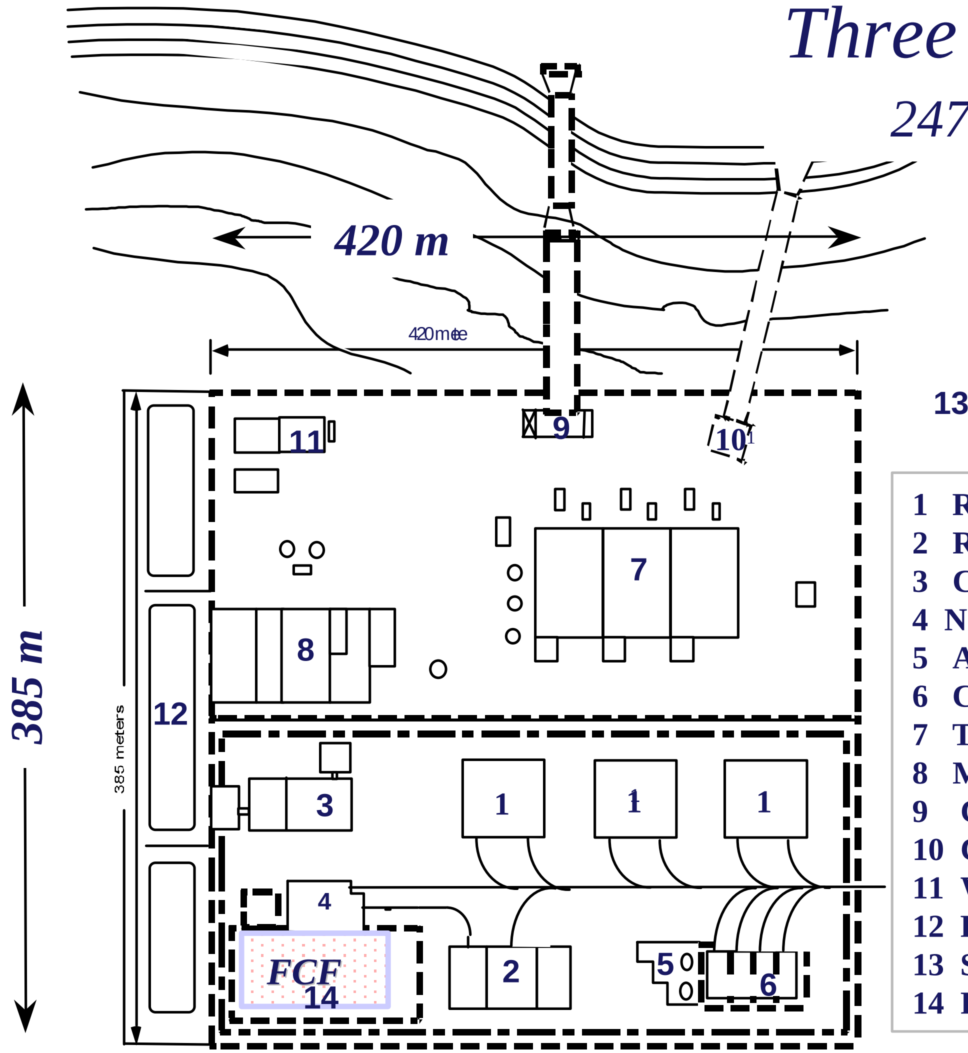
- *Attractive features of metal core include:*
  - *fuel is denser and has a harder neutron spectrum*
  - *compatible with coolant, RBCB demonstrated at EBR-II*
  - *axial blankets are not required for break even core*
  - *high thermal conductivity (low fuel temp.)*
  - *lower Doppler and harder spectrum reduce the need for GEMs for ULOF (6 versus 18)*
- *Metal fuel pyro-processing is diversion resistant, compact, less complex, and has fewer waste streams than conventional aqueous (PUREX) process*
- *However, an "advanced" aqueous process may be competitive and diversion resistant.*

S-PRISM can meet all requirements with either fuel type.

S-PRISM - Three Power Block Plot Plan

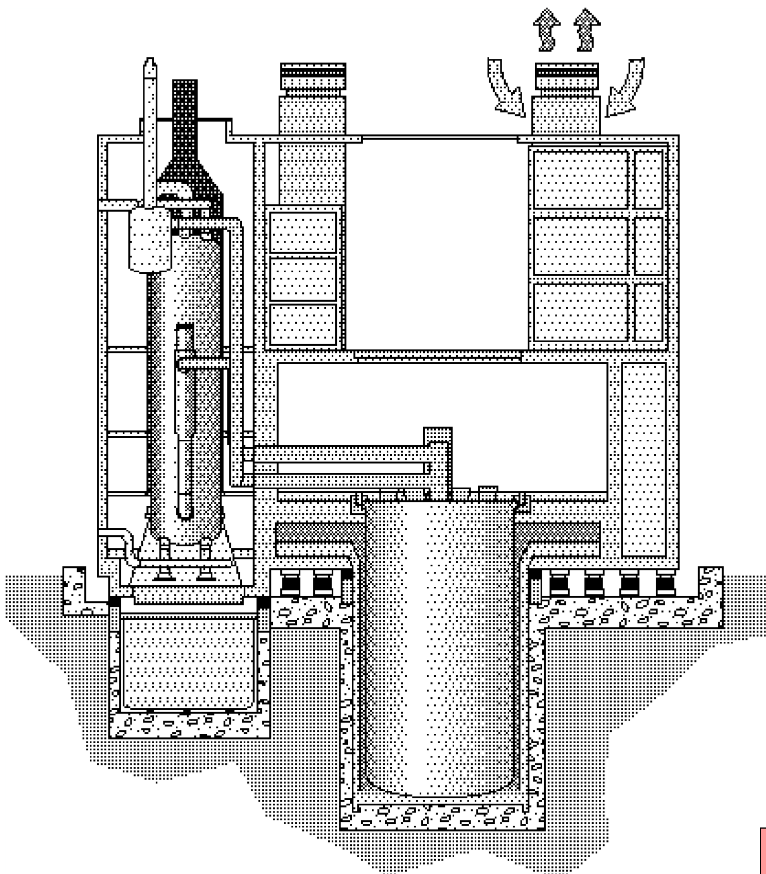
Three Power Block Plant

2475 MWe (2280 MWe net)



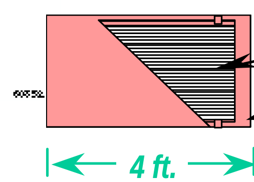
1 Reactor Building (2 NSSS/block)
2 Reactor Maintenance Facility
3 Control Facility
4 New and Spent Fuel Handling Facility
5 Assembly Facility
6 Cask Storage Facility
7 Turbine-Generator Facility
8 Maintenance Facility
9 Circulating Water Inlet Pump Station
10 Circulating Water Discharge
11 Waste Treatment
12 Parking Lot
13 Switch Yard
14 Fuel Cycle Facility

S-PRISM - Seismic Isolation System



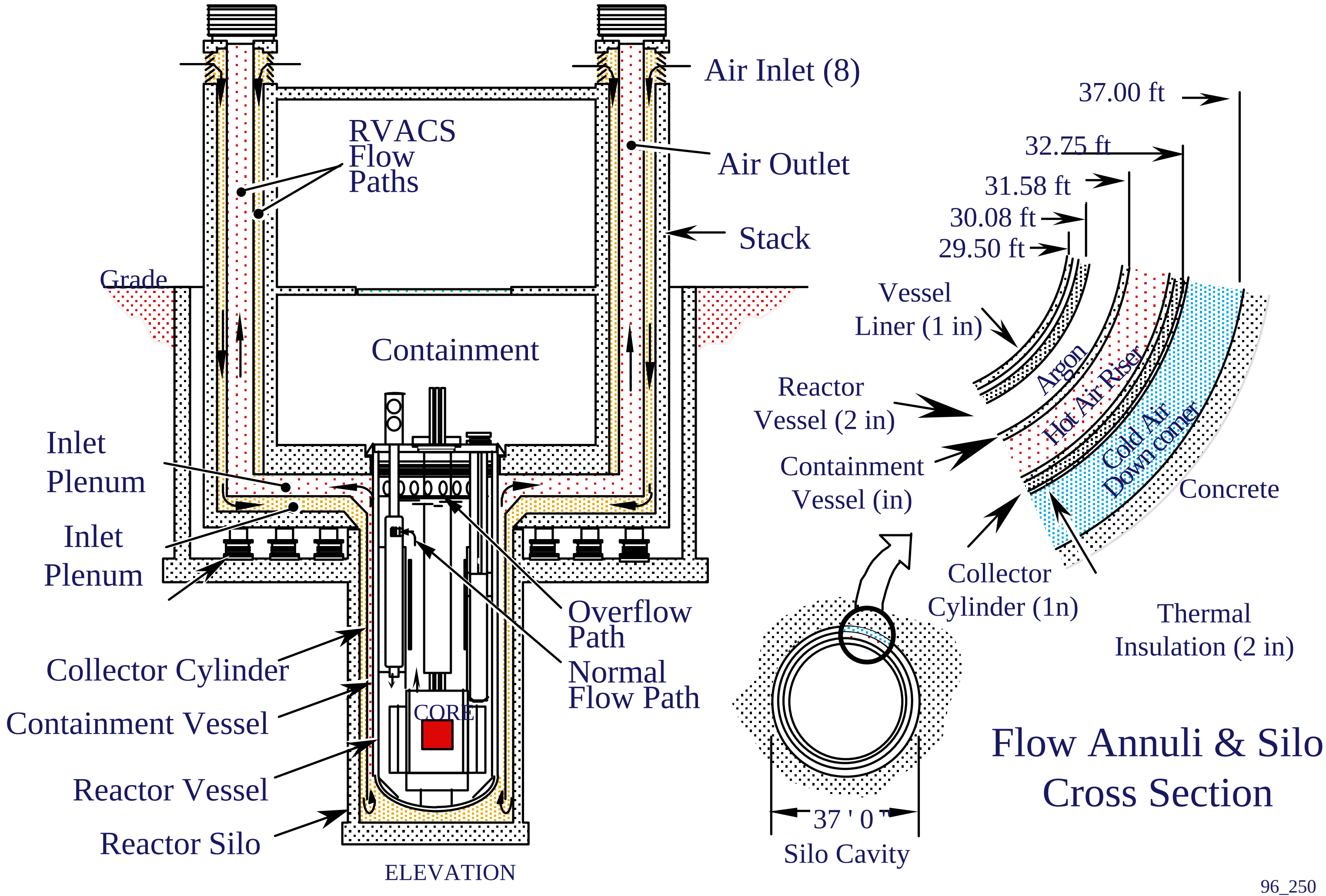
Characteristics of Seismic Isolation System

- *Safe Shutdown Earthquake*
  - *Licensing Basis* 0.3g (ZPA)
  - *Design Requirement* 0.5g
- *Lateral Displacement*
  - *at 0.3g* 7.5 inch.
  - *Space Allowance*
    - *Reactor Cavity* 20 inch.
    - *Reactor Bldg.* 28 inch.
- *Natural Frequency*
  - *Horizontal* 0.70 Hz
  - *Vertical* 21 Hz
- *Lateral Load Reduction > 3*

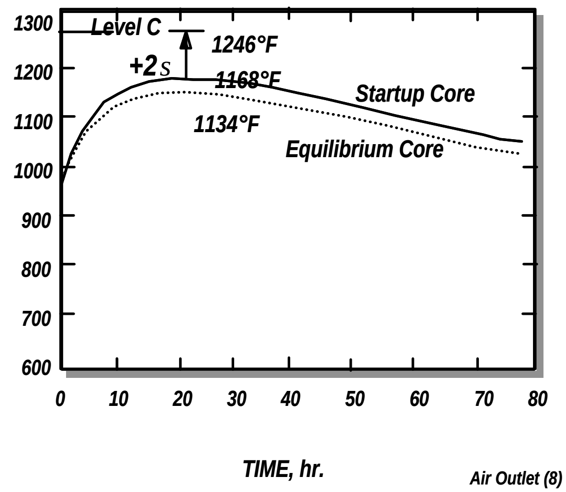


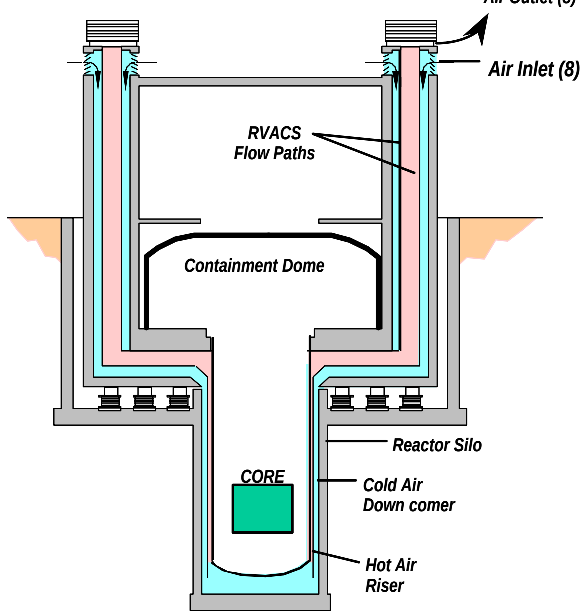
Seismic Isolators (66)

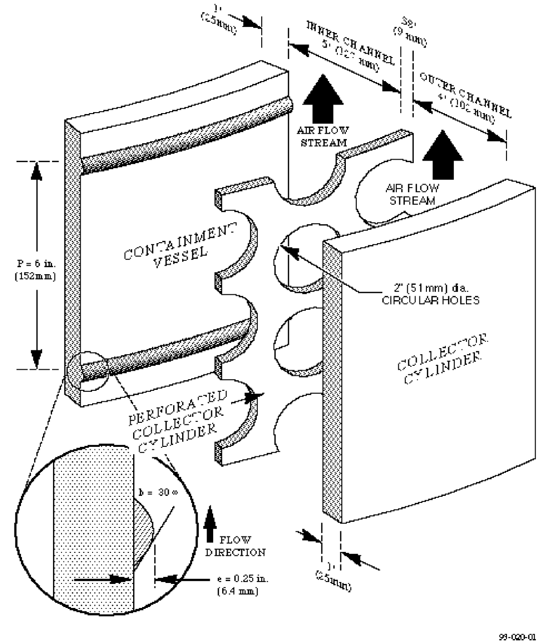
Reactor Vessel Auxiliary Cooling System (RVACS)



Passive Shutdown Heat Removal (RVACS)

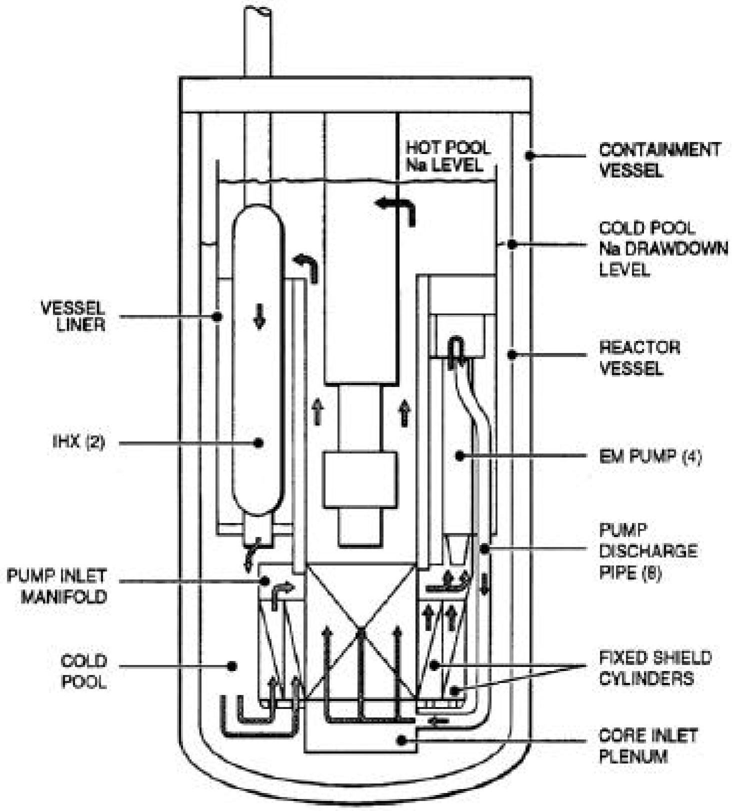




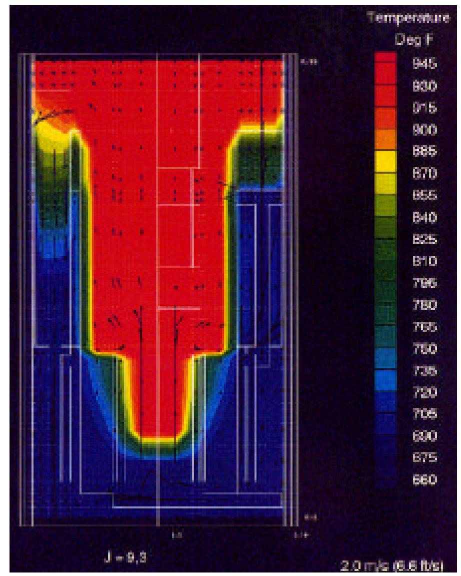


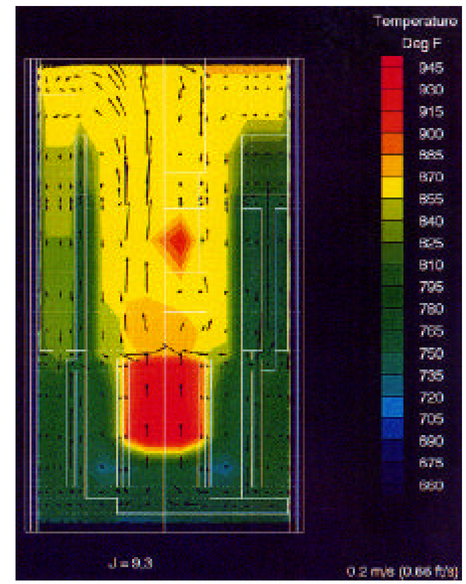
ENHANCED RVACS HOT AIR RISER WITH BOUNDARY LAYER TRIPS AND PERFORATED COLLECTOR CYLINDER

Natural Circulation Confirmed by 3 Dimensional T/H Analysis



Normal Operation

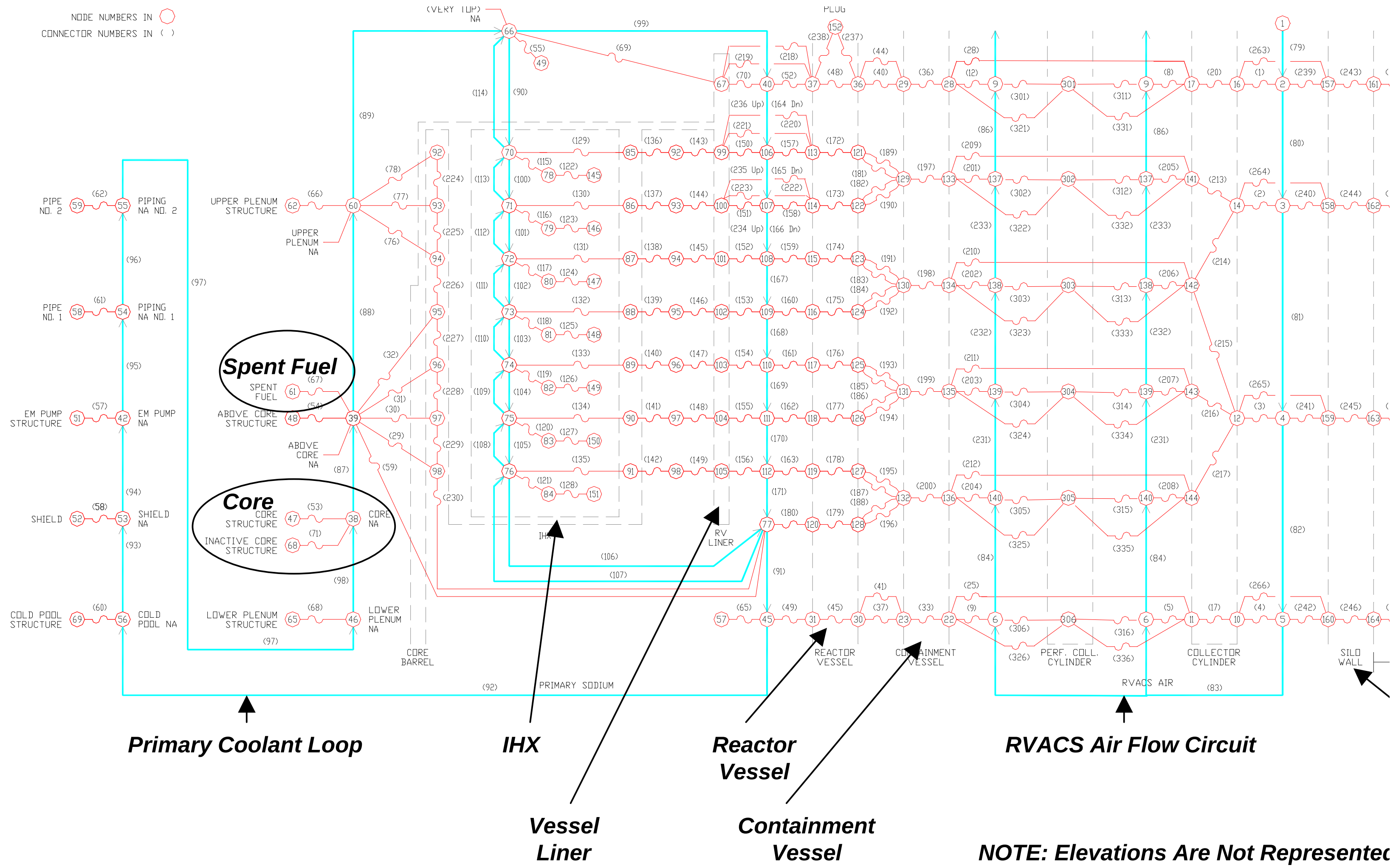




<u>Examples</u>

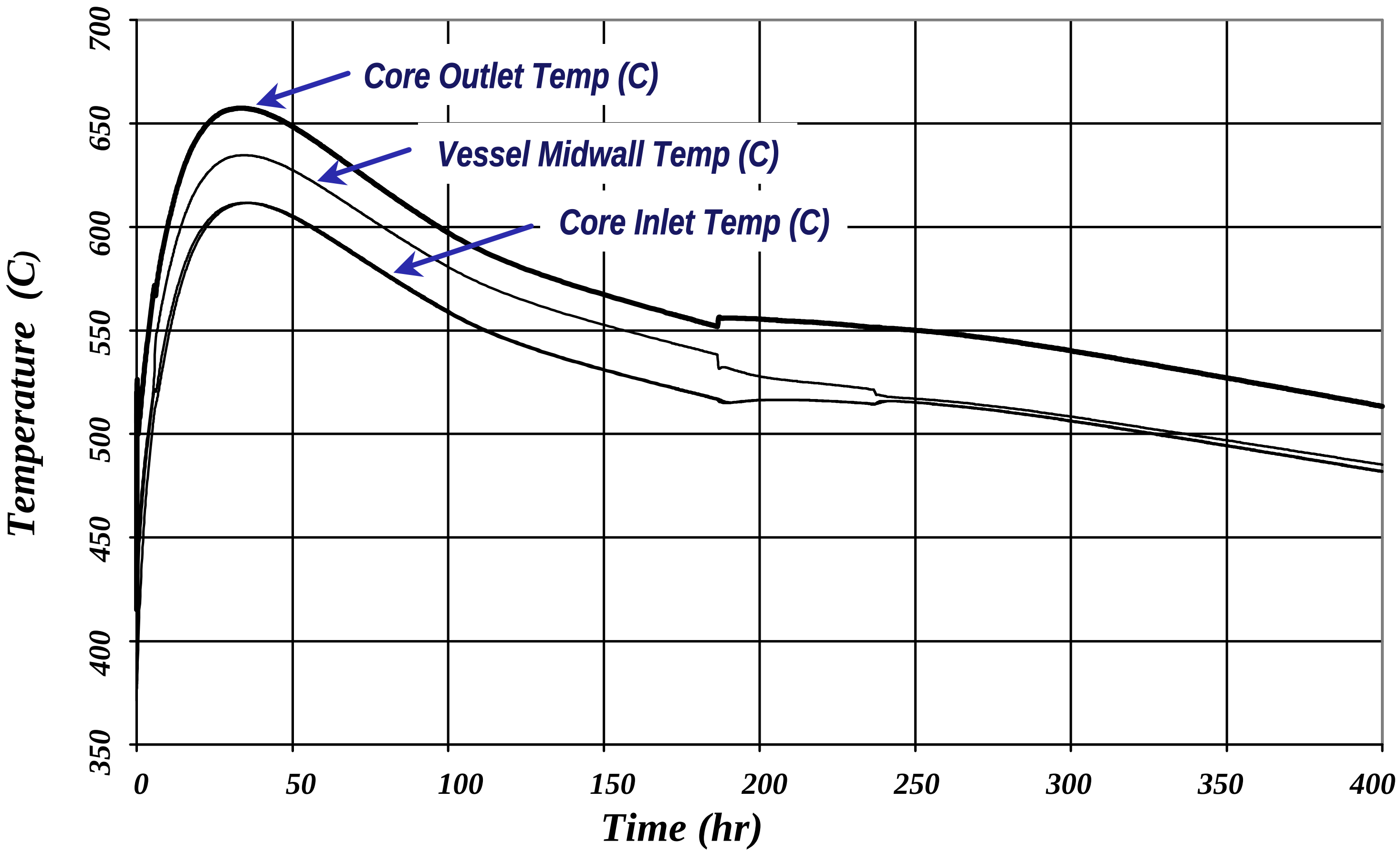
Temperature and velocity distribution
at 4 and 20 minutes after loss of heat sink

Decay Heat Removal Analysis Model



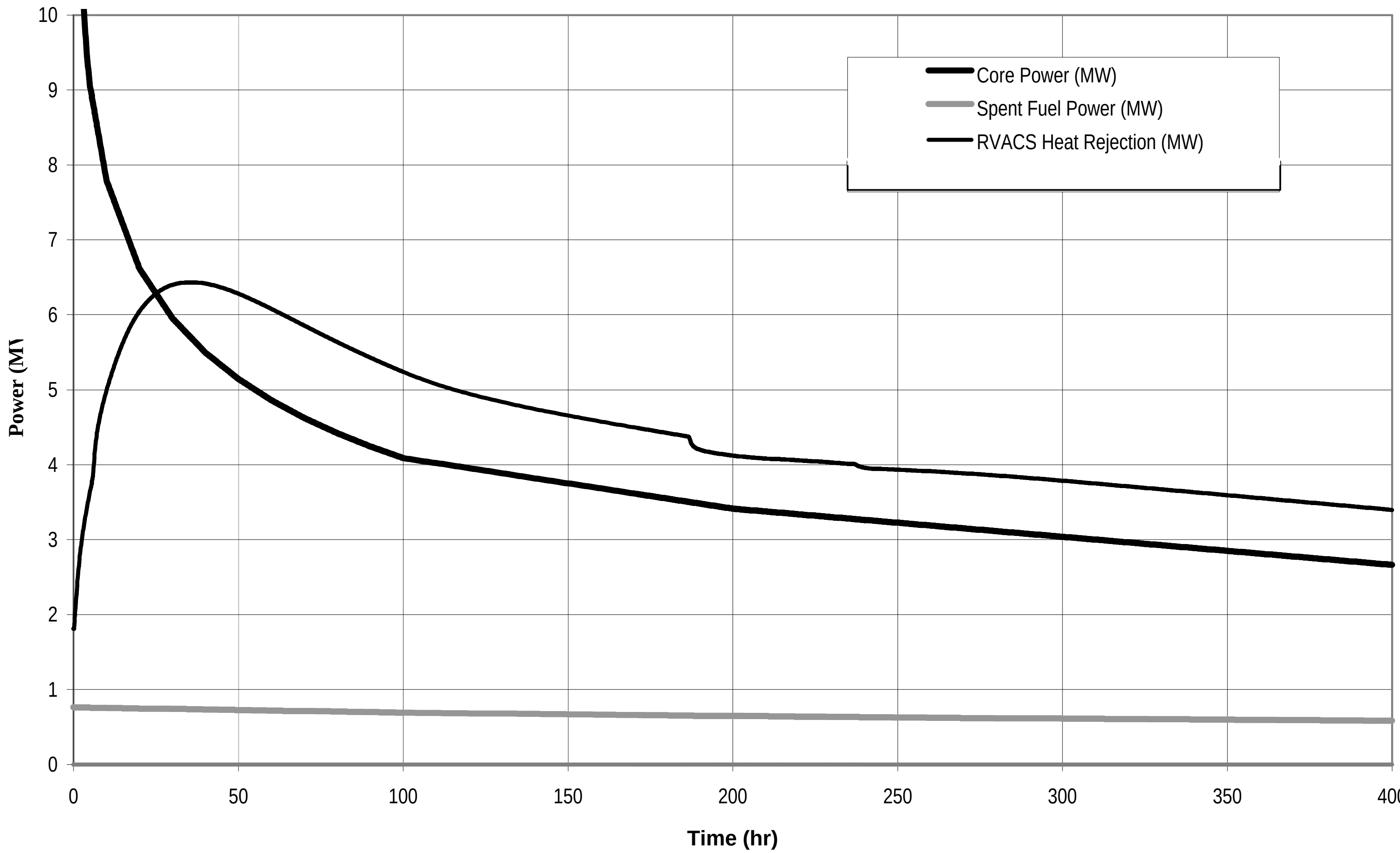
NOTE: Elevations Are Not Represented

RVACS Cooling - Nominal System Temperatures

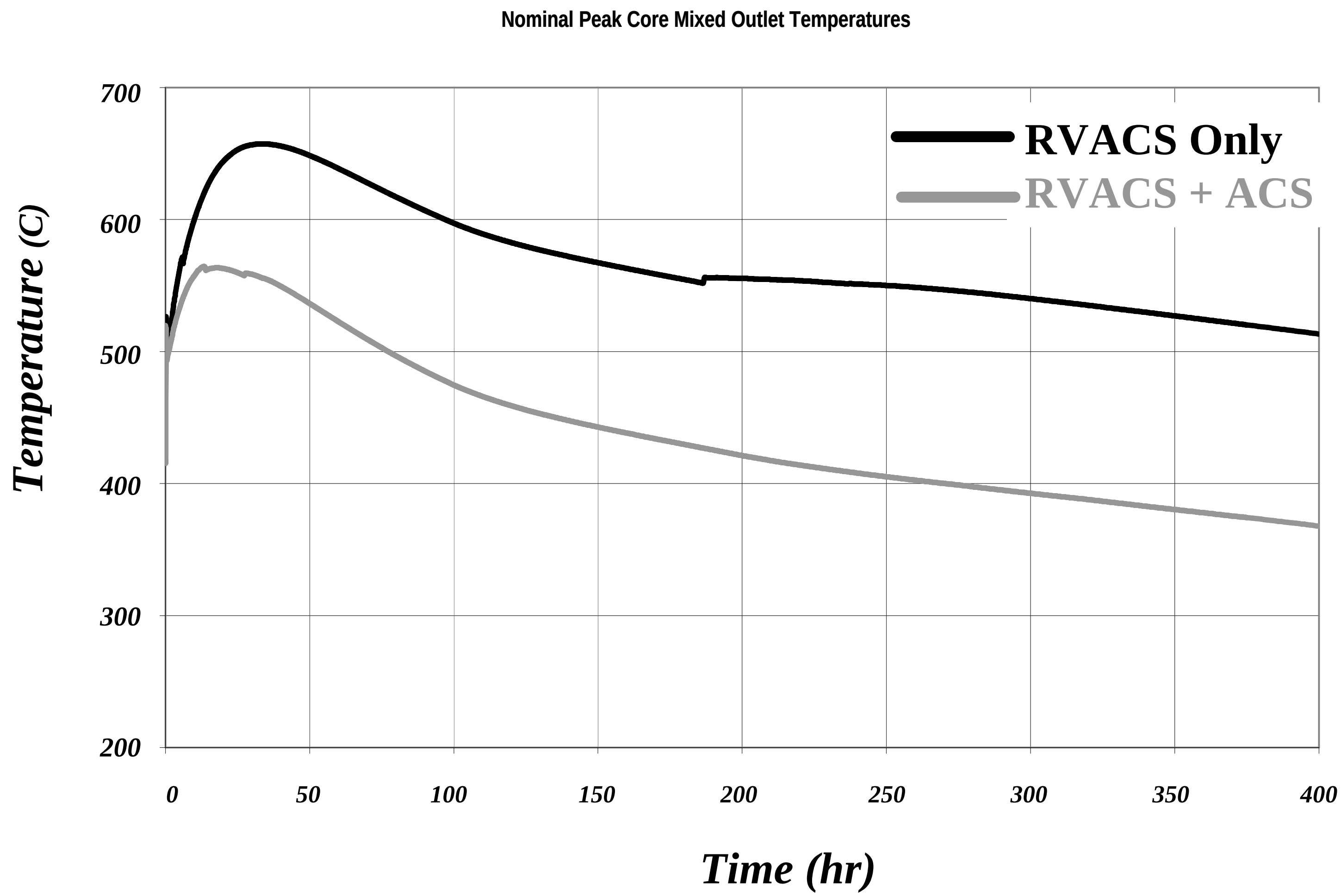


RVACS Transients Are Slow Quasi Steady State Events

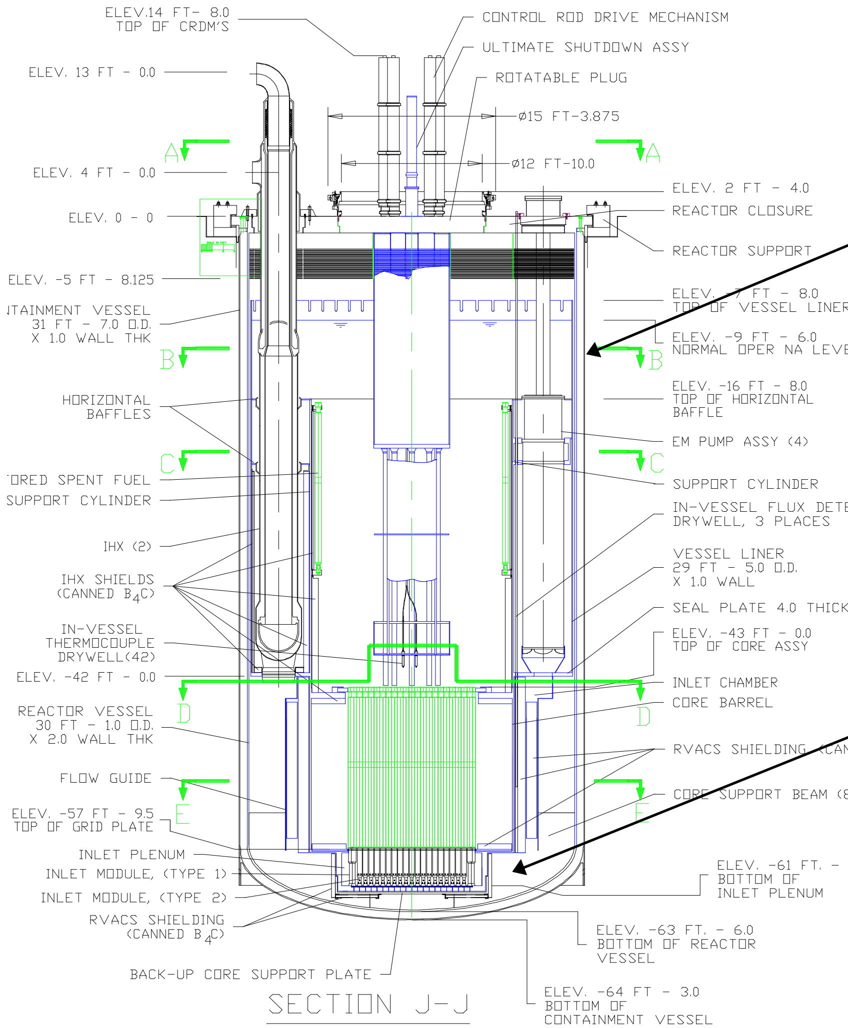
RVACS Heat Rejection and Heat Load versus Time



RVACS Cooling - Nominal Mixed Core Outlet Temperature



Damage Fraction *from* *__Six__ RVACS Transients*



Peak Temperature & Damage Fraction at __Vessel Mid Wall__ (nominal / 2-sigma)

Temperature °C	Damage Fraction
635 / 683	<0.002 / 0.002

Peak Temperature & Damage Fraction at __Core Support__ (nominal / 2-sigma)

Temperature (°C)	Damage Fraction
612 / 658	<0.002 / 0.002

Damage from RVACS Transients Is Negligible

S-PRISM Approach to ATWS

Negative temperature coefficients of reactivity are used to accommodate ATWS events.

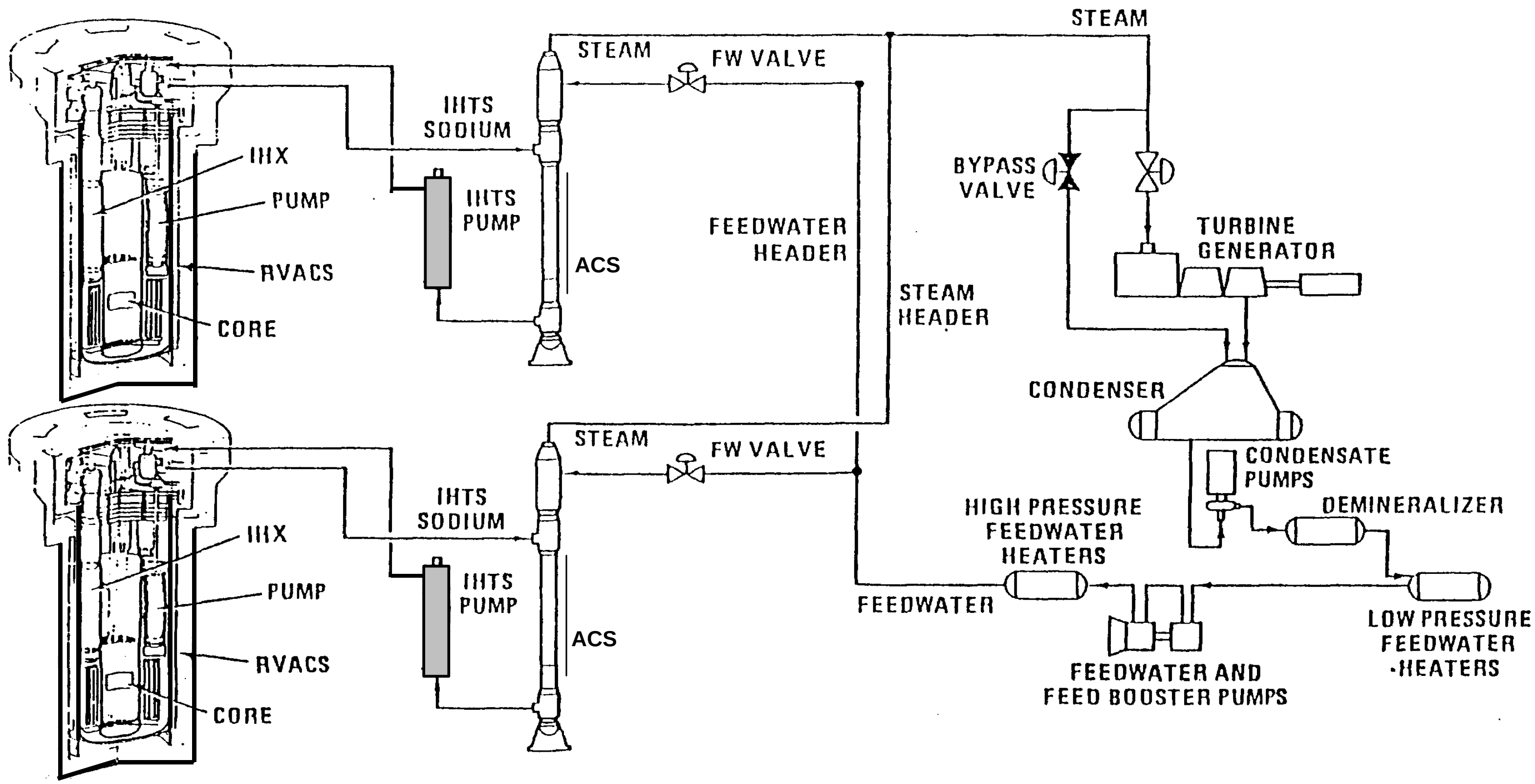
- *Loss of Normal Heat Sink*
- *Loss of Forced Flow*
- *Loss of Flow and Heat Sink*
- *Transient Overpower w/o Scram*

These events have, in priorLMR designs, led to rapid coolant boiling, fuel melting, and core disassembly.

S-PRISM Requirement:

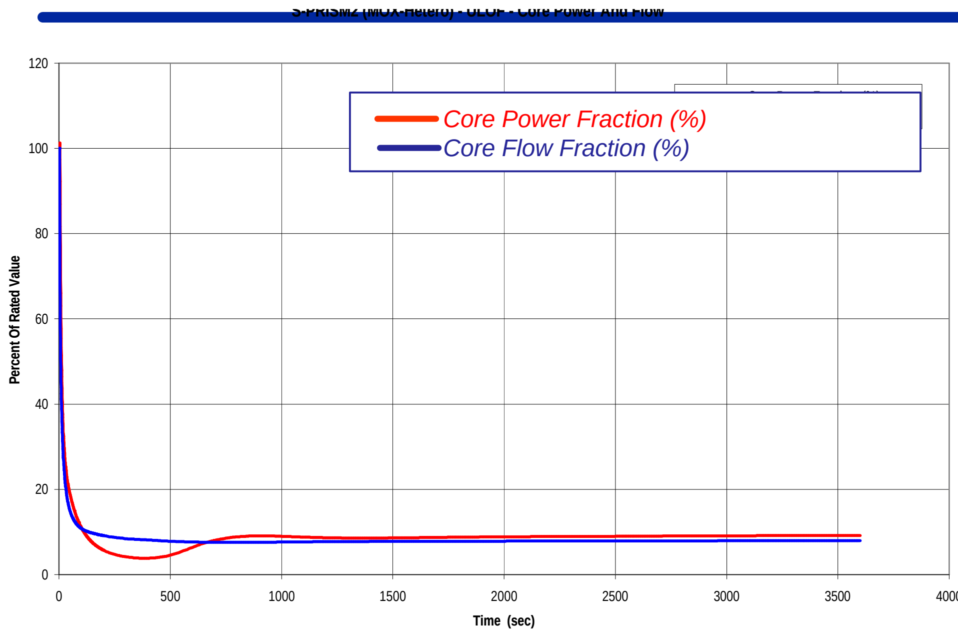
Accommodate the above subset of events w/o loss of reactor integrity or radiological release using passive or inherent natural processes. A loss of functionality or component life-termination is acceptable.

ARIES-P Power Block Transient Model



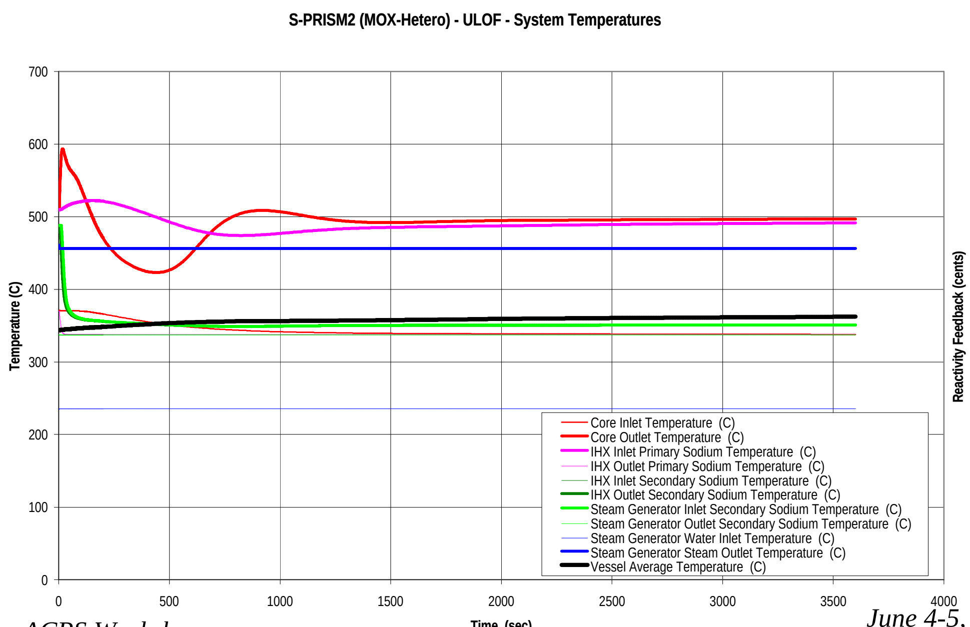
- *Two-Reactors Coupled to a Single TG*
- *One Group Prompt Jump Core Physics with Multi-Group Decay Heat*
- *RVACS/ACS*
- *Once-through Superheat*
- *Control Systems:*
  - *Plant control system (global and local controllers)*
  - *Reactivity control system (RCS)*
  - *Reactor protection system (RPS)*
  - *EM pump control system and synchronous machines*

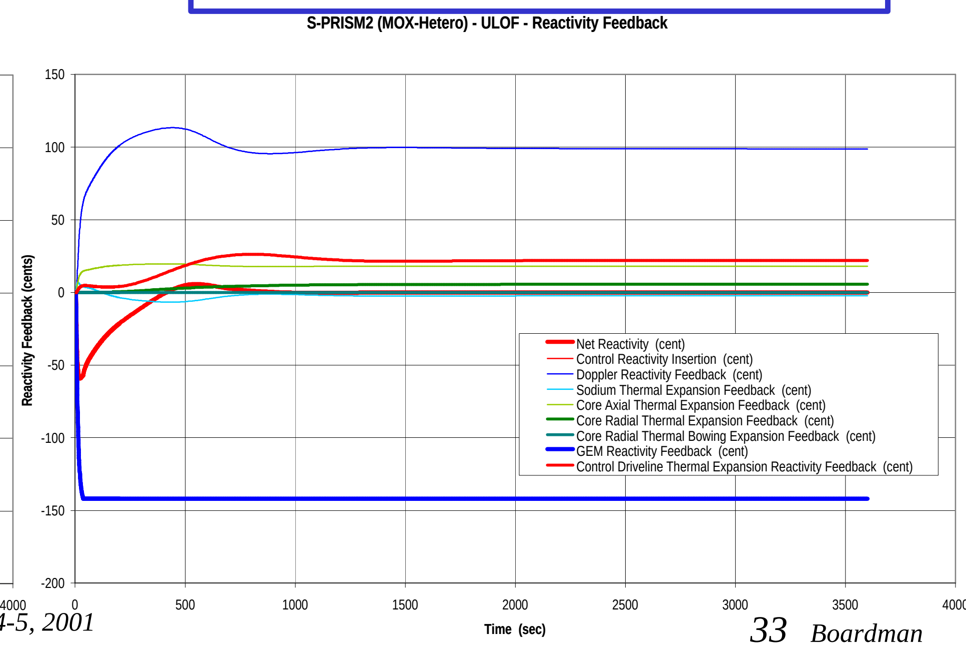
Example ATWS - Loss Of Flow Without Scram



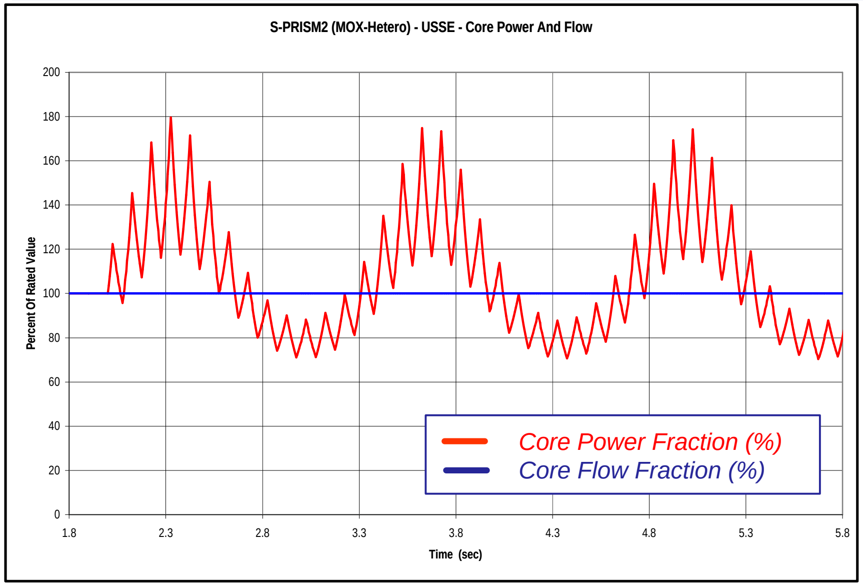
Loss of Primary Pump Power w/o Scram

- ***Loss of pump pressure allows GEM feedback and fission shutdown***
- ***Continuation of IHTS flow and feed water water enhance primary natural circulation to 10%***
- ***Excess cooling of core outlet shortens CR drivelines and pulls control rods slightly to balance fission power with heat removal***





Example - 0.5 g ZPA Seismic Event Without Scram

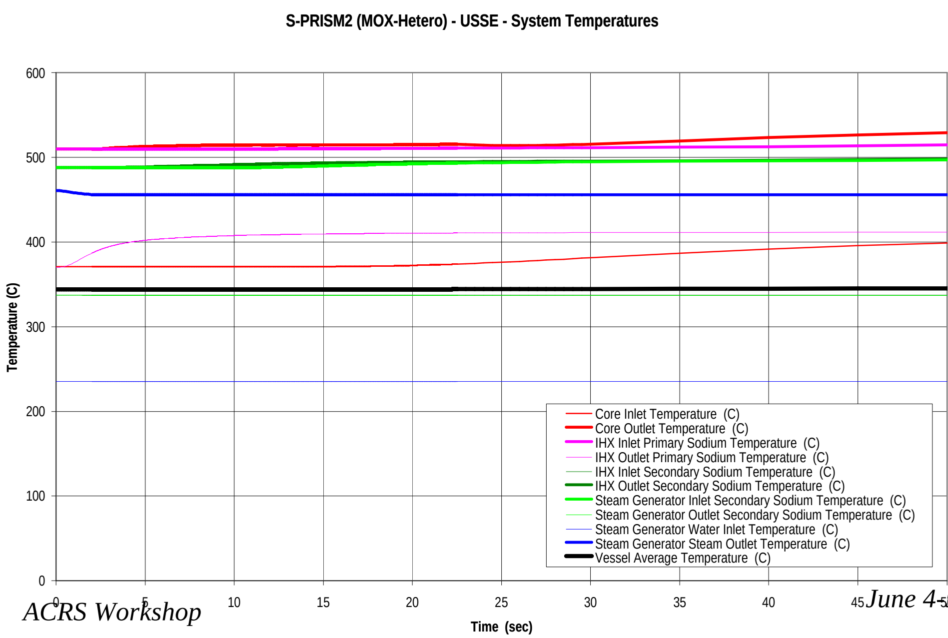


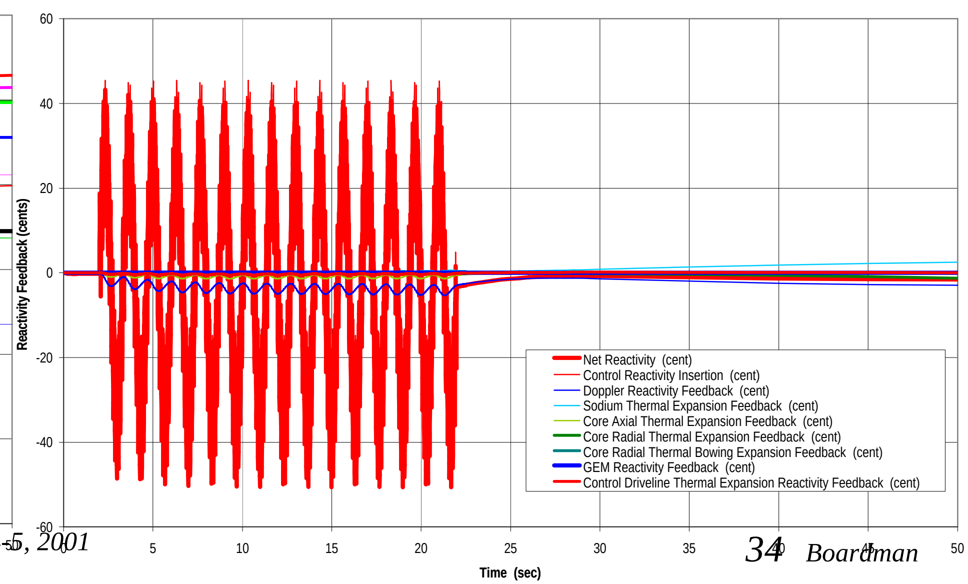
- **Reactivity:**

  + - 0.30$ at 3/4 Hz (horizontal core compaction)

  + - 0.16$ at 10 Hz (vertical CR-core motion with opposite phases)

- ***Power oscillations to 180%, short duration, not supercritical***
- ***Fuel heat capacity absorbs power oscillation without melting***
- ***Fuel releases heat to structures slowly and gives small Doppler feedback to reduce power peaks***



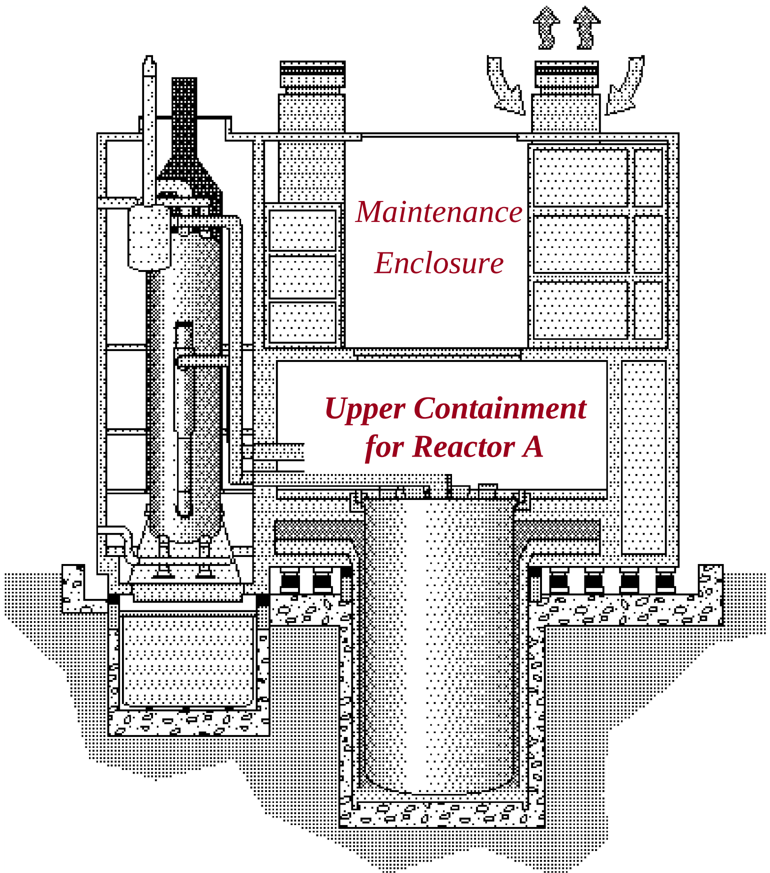


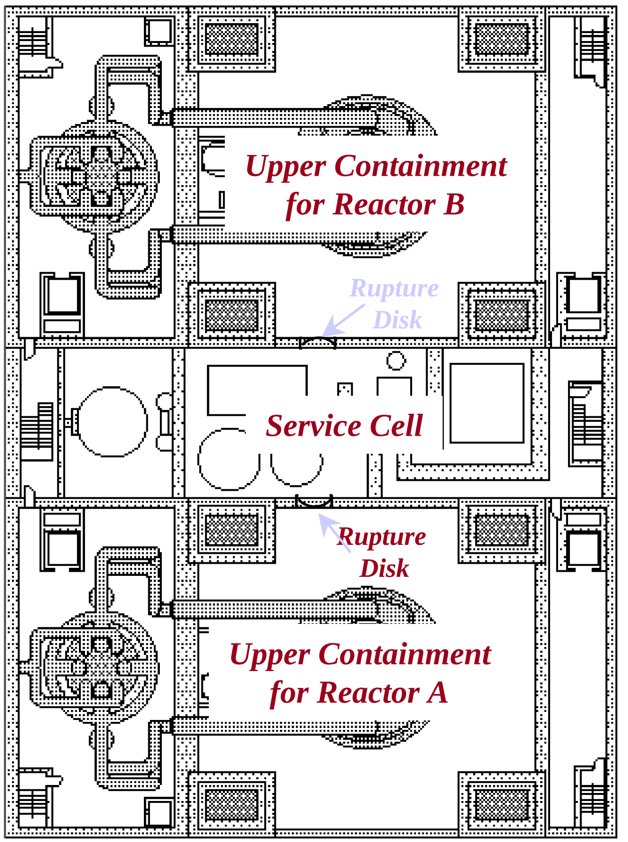
S-PRISM Transient Performance Conclusions

S-PRISM tolerates ATWS events within the safety performance limits

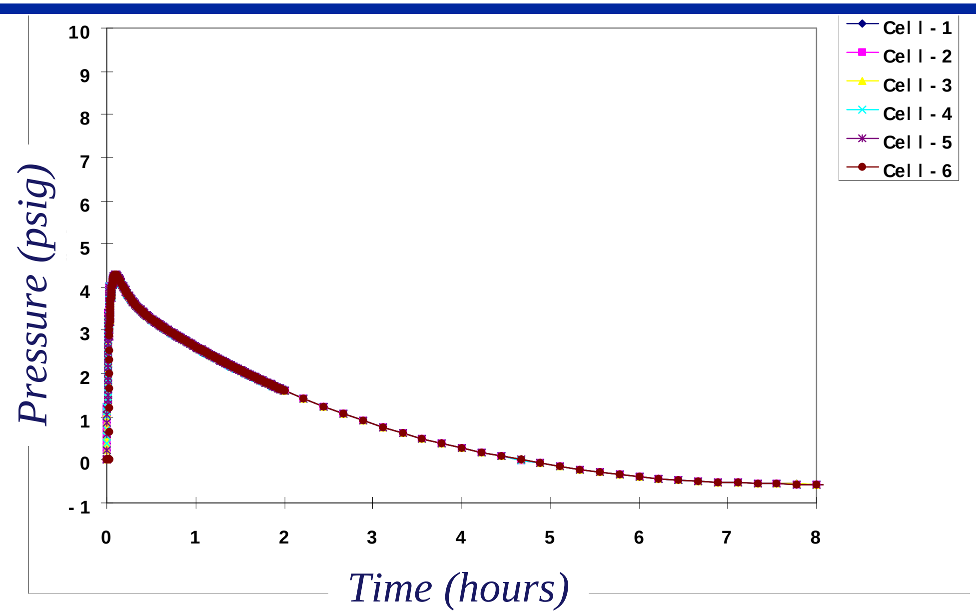
The passive safety performance of S-PRISM is consistent with the earlier ALMR program

S-PRISM Containment System





Example - Large Pool Fire



Beyond Design Basis (Residual Risk)
events have been used to assess containment margins

This event assumes that the reactor closure disappears at time zero initiating a large pool fire

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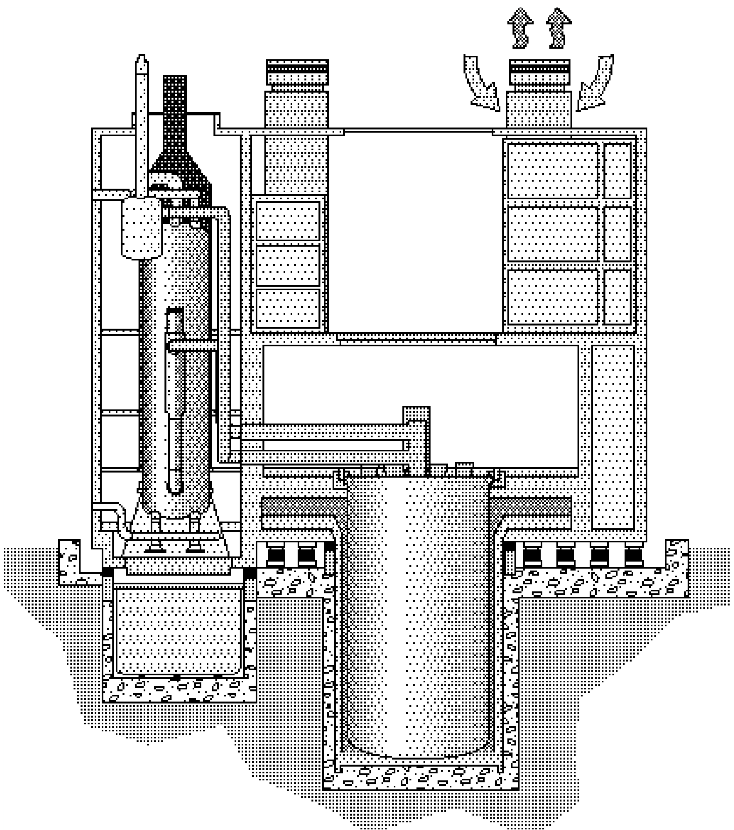
Note that the containment pressure peaks at less than 5 psig and drops below atmospheric pressure in less than 6 hours

Comparison of Emergency Power Requirements

Function	S-PRISM	Generation III LWRs
● Shutdown Heat Removal	Completely Passive	Redundant and Diverse Systems
● Post Accident Containment Cooling	Passive Air Cooling of Upper Containment	Redundant and Diverse Systems
● Coolant Injection/Core Flooding	N/A	Redundant and Diverse Systems
● Shutdown System	3/9 Primary or 2/3 Secondary Rods	Most Rods Must Function
	Self Actuated Scram on Secondary Rods	Boron injection
	Passive Accommodation of ATWS Events	N/A

Emergency AC Power	< 200 kWe from Batteries	~ 10,000 kWe

Layers of Defense



All Safety Grade Systems Are Located within the Reactor/NSSS Building

- ***Containment***
  (passive post accident heat removal)
- ***Coolant Boundary (Reactor Vessel***
  (simple vessel with no penetrations below the Na level)
- ***Passive Shutdown Heat Removal***
  (RVACS + ACS)
- ***Passive Core Shutdown***
  (inherent negative feedback's)
- ***RPS Scram of Scram Rods***
  (magnetic Self Actuaed Latch backs up RPS)
- ***RPS Scram of Control Rods***
  (RPS is independent and close coupled)
- ***Automatic Power Run Back***
  (by automated non safety grade Plant Control System

Increasing Challenge

Normal Operating Range

- ***Maintained by Fault Tolerant Tri-Redundant Control System***

Adjustments Since End of DOE Program In 1995

Parameter or Feature	1995 ALMR	S-PRISM
Core Power, MWt	840.	1000.
Core Outlet Temp, °C	499	510
Main Steam, °C / kg/cm^2	454/153	468/177
Net Electrical, MWe (two power blocks)	1243.	1520
Net Electrical, MWe (three power blocks)	1866	2280
Seismic Isolation	Yes. Each NSSS placed on a separate isolated platform	Yes. A single platform supports two NSSSs
Above Reactor Containment	Low leakage steel machinery dome	Low leakage steel lined compartments above the reactor closure

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Optimizing the Plant Size

1988 PRISM → ***S-PRISM***

1263 MWe (net) from 3 blocks
9 NSSS (425 MWt each)
3 421 MWe TG Units
9 primary Na containing vessels
9 SG units/eighteen IHTS loops

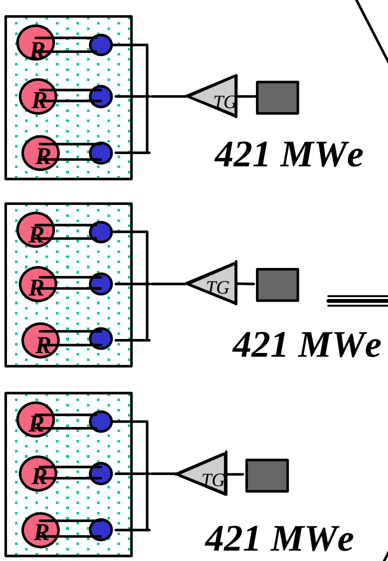
1520 MWe (net) from two blocks
4 NSSS (1000 MWt each)
2 825 MWe (gross) TG Units
4 primary Na containing vessels
4 SG units and eight IHTS loops
(1000/500 MWt each)

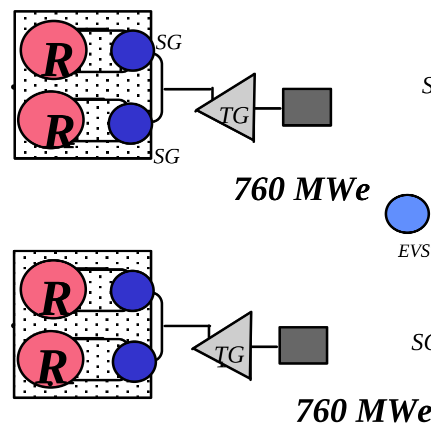
- -

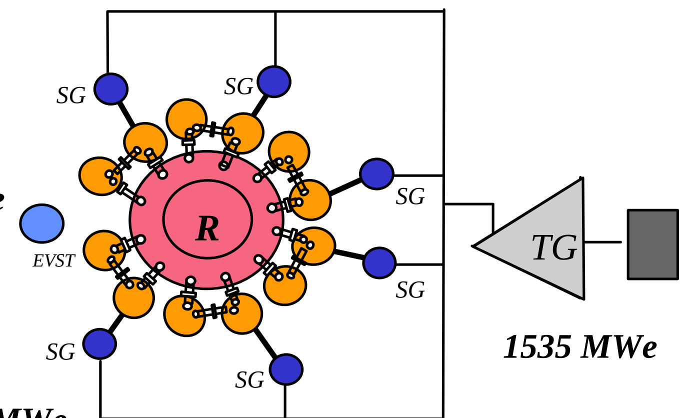
Larger module (1000 vs. 425 MWt)
Once through superheat steam cycle

Large Commercial Design

1,535 MWe Monolithic LMR
1 NSSS (4000 MWt)
1 1535 MWe TG Unit
14 primary Na containing vessels*
(12 primary component vessels, reactor, and EVST)
6 SG units and 6 IHTS loops (667 MWt each)
4 Shutdown Heat Removal Systems
(DHX/IHX units, pump, piping, and support systems)
- Redundant SHRS also required for EVST



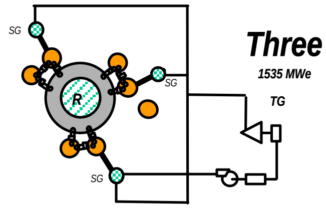




Simplicity allows Reduction in Commodities and Building Size

Scale Up - - LWR versus Fast Reactor

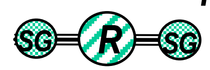
1600 MWt Sodium Cooled Fast Reactor



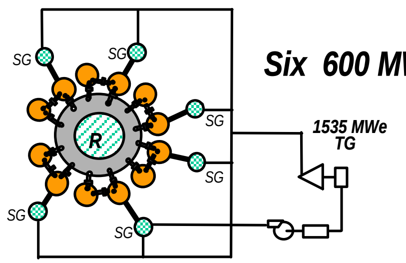
Three 533 MWt Loops

1600 MWt Light Water Cooled Reactor

Two 800 MWt Loops



3600 MWt FR

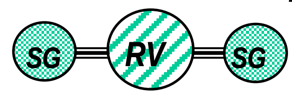


Six 600 MWt Loops

Rating Limited by:
IHTS Piping: < 1 m diameter

3600 MWt PWR

Two 1800 MWt Loops

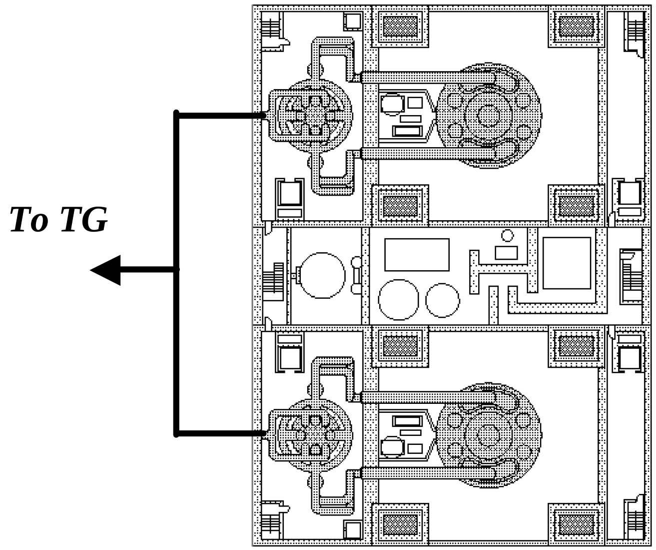


Two Loops Viable Because:
Specific heat of water 5 x sodium at operating temperatures

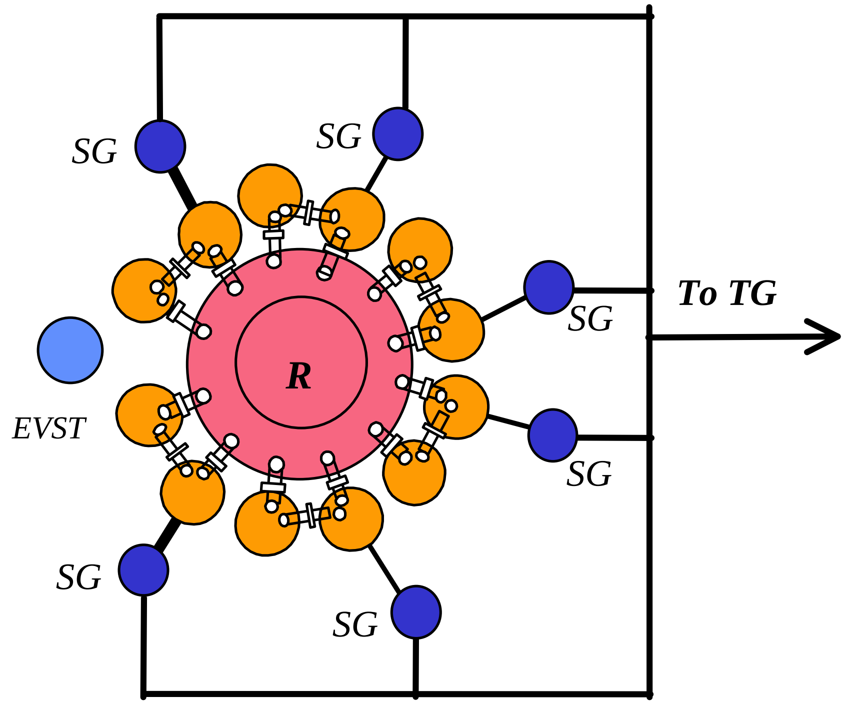
- ***The complexity and availability of a PWR is essentially constant with size***
- ***Due to the lower specific heat of sodium, six or more loops are required in a large FR.***

The Economy of Scale is Much Larger for LWRs then FBRs

Modular versus Monolithic *(Fast Reactors)*



Modular (S-PRISM)

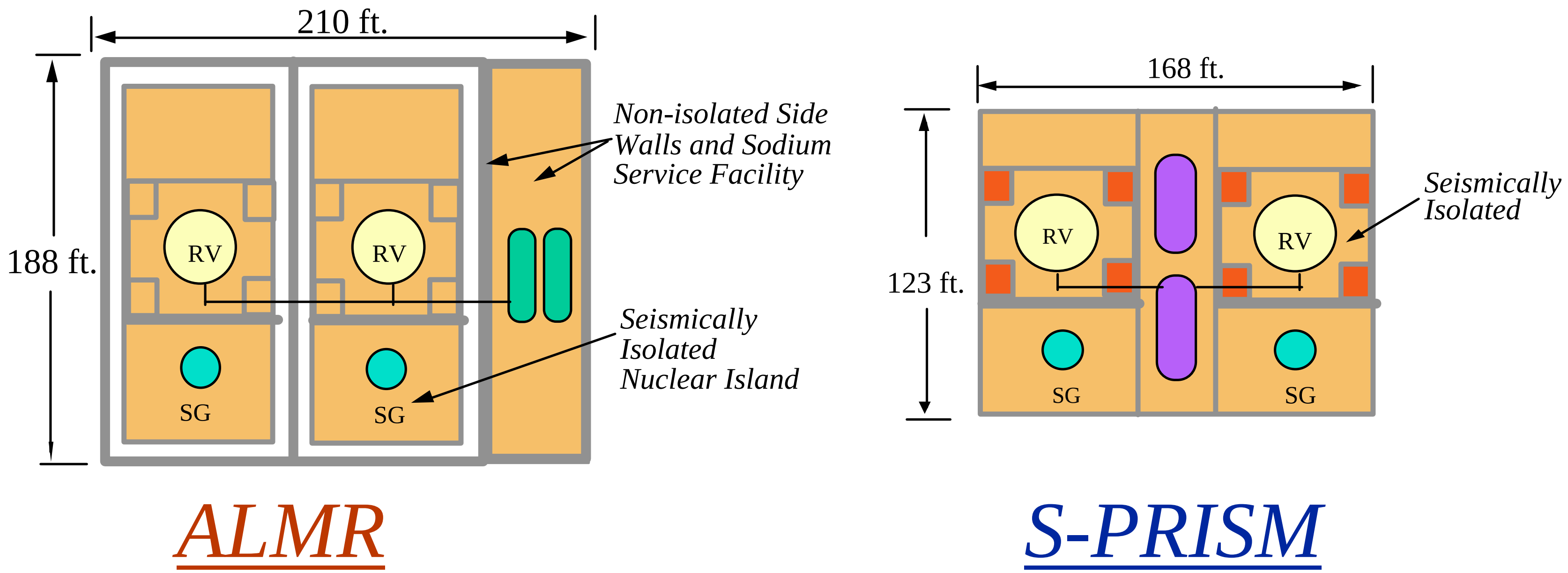


Monolithic Fast Reactor

The one-on-one arrangement:

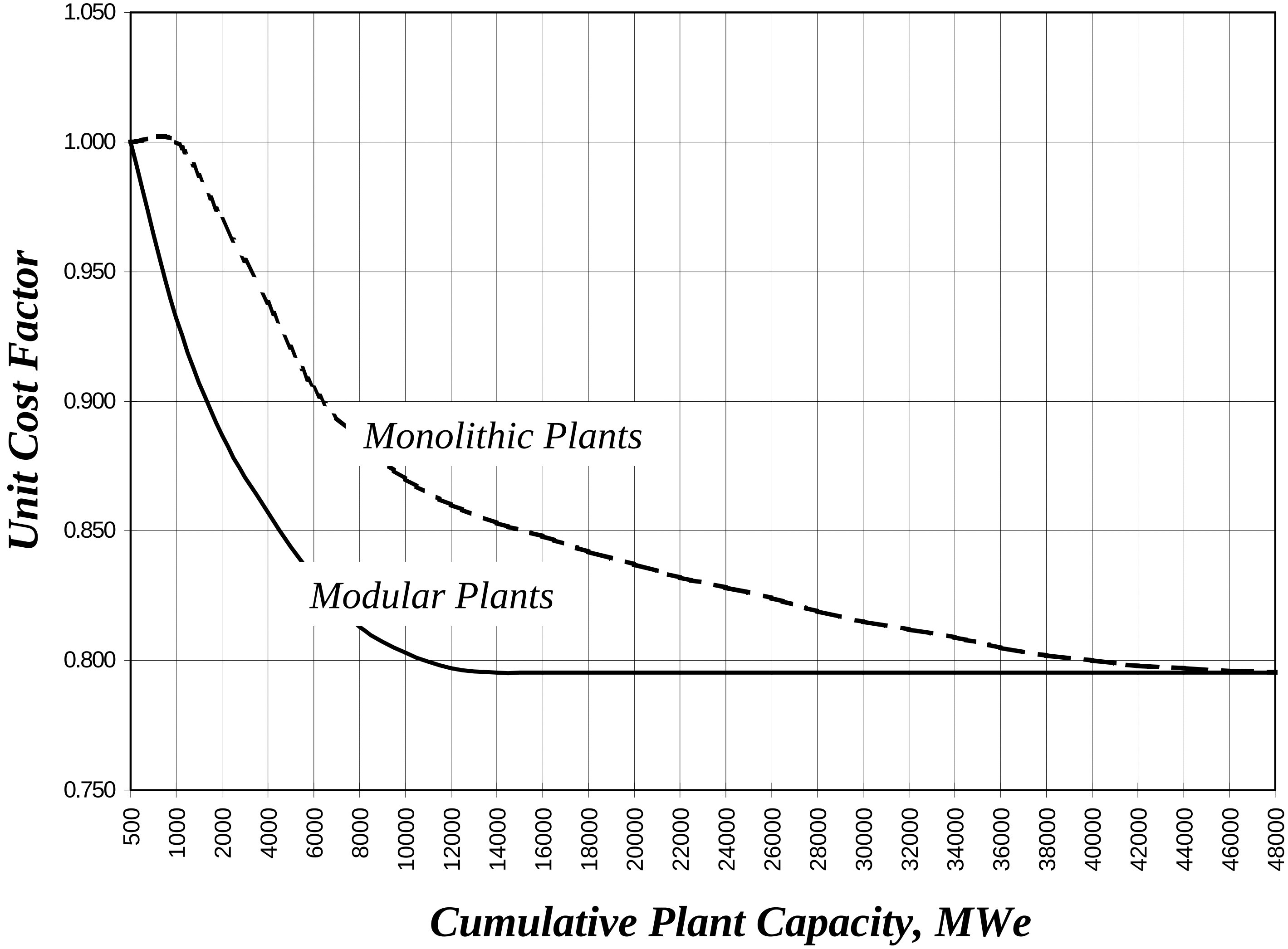
- *simplifies operation,*
- *minimizes the size of the reactor building*
- *improves the plant capacity factor*
- *reduced the need for backup spinning reserve*

NSSS Size, ALMR versus S-PRISM

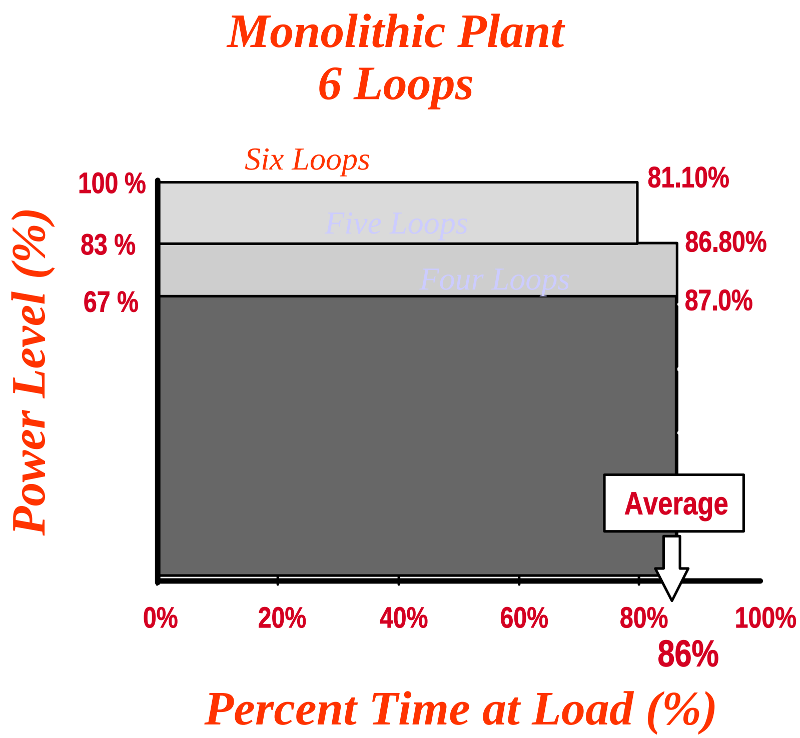


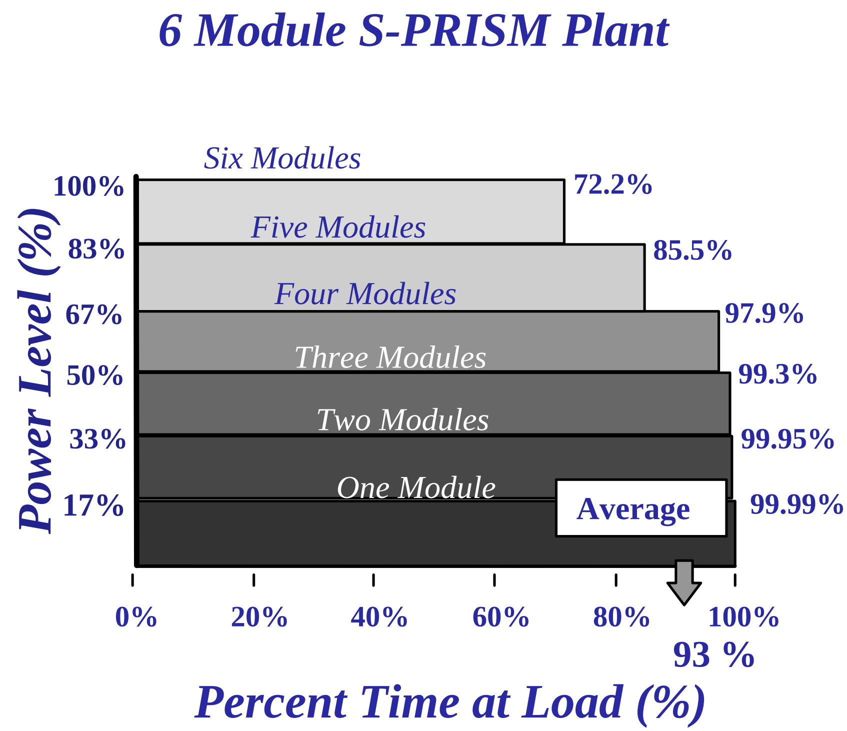
22 % More Power from Smaller NI

Learning Effect Favors Modular Plant Designs



Modular vs. Monolithic Availability and Spinning Reserve

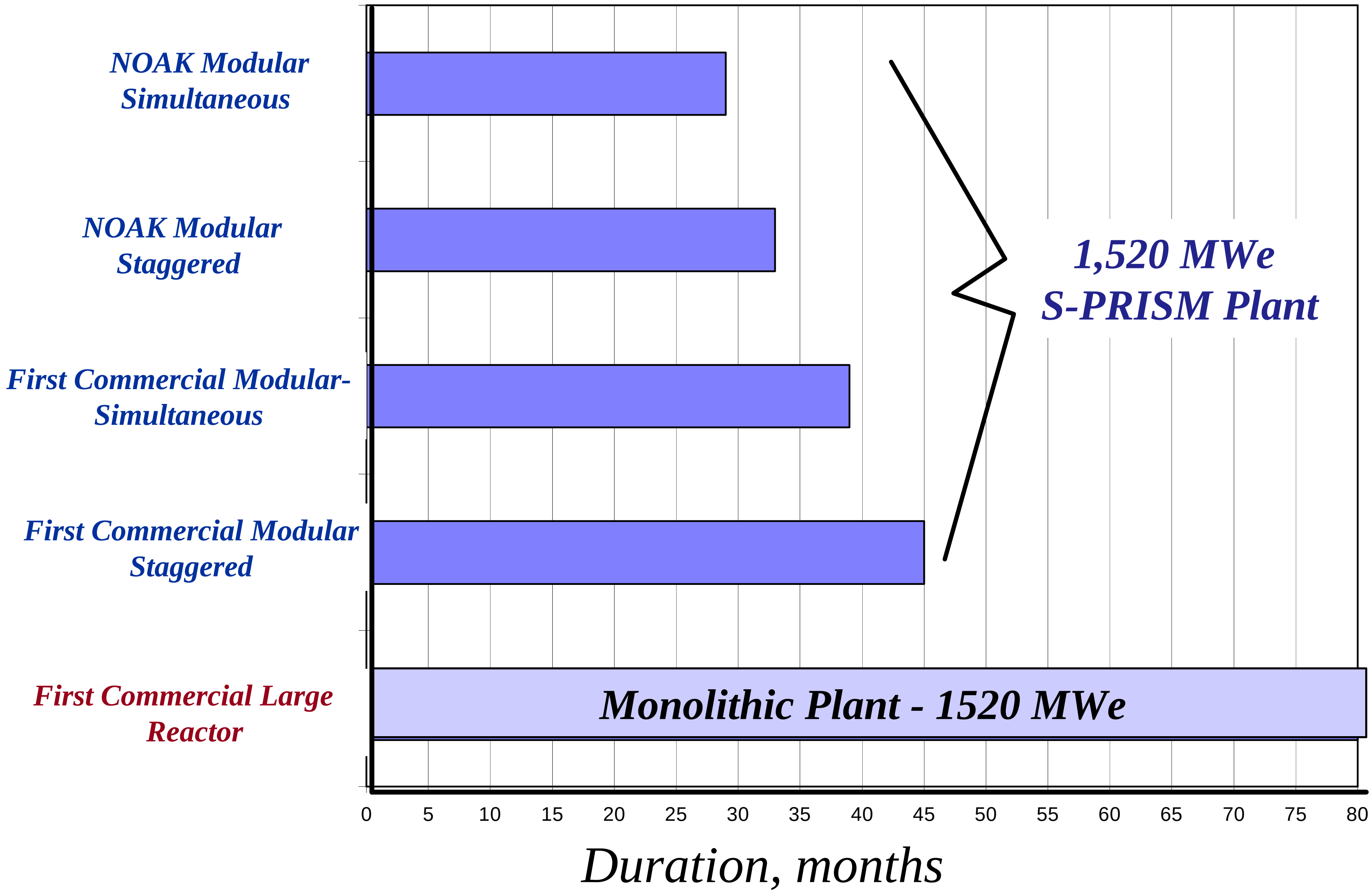




Seven point advantage caused by:

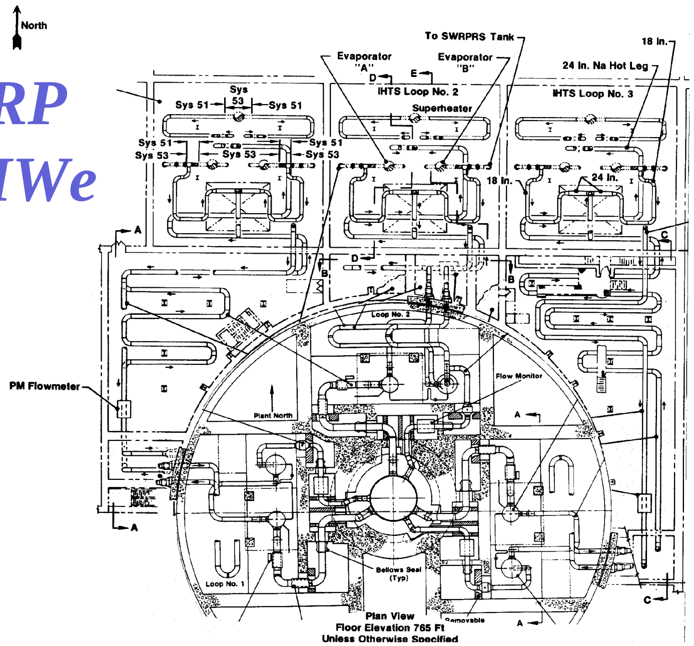
- *Relative simplicity of each NSSS (one SG System rather than 6)*
- *Ability to operate each NSSS independently of the others*

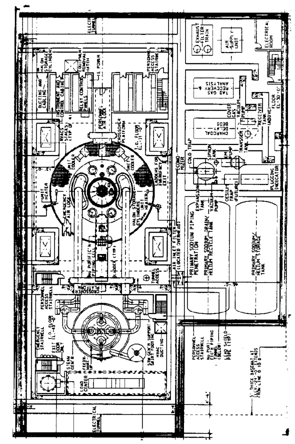
Comparison of Plant Construction Schedules



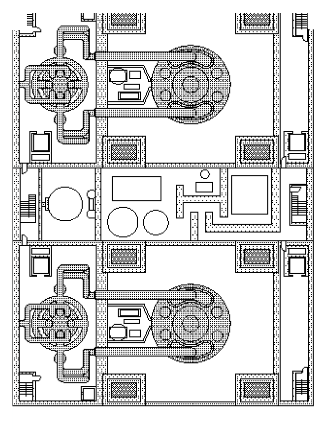
NSSS Size, CRBRP/ALMR /S-PRISM

CRBRP
350 MWe





ALMR
311 MWe



S-PRISM
760 MWe

The commodities required to build S-PRISM have been reduced by a factor of > 5

Topics

- *Incentive for developing S-PRISM*
- *Design and safety approach*
- *Design description and competitive potential*
- *Previous licensing interactions*
- *Planned approach to licensing S-PRISM*
- *What , if any, additional initiatives are needed?*

ALMR Design and Licensing History

1981 - 1984

GE PRISM Program

GE Funded

Innovative Design Studies

1985 - 1987

PRISM

- $ 30 M

Competition for National Program

1988

PRDA

- $ 5 M

Continue Trade Studies

1989 - 1995

ALMR PROGRAM

- $ 42 M
- Advanced. Conceptual & Preliminary Design
- ***Regulatory Review***
- Economic Reviews
- Commercialization Studies
- Technology Development ($107 M Additional)

$ 77 Million DOE Program

1995

S-PRISM

GE Funded

S-PRISM is supported by a 100 million dollar Data Base

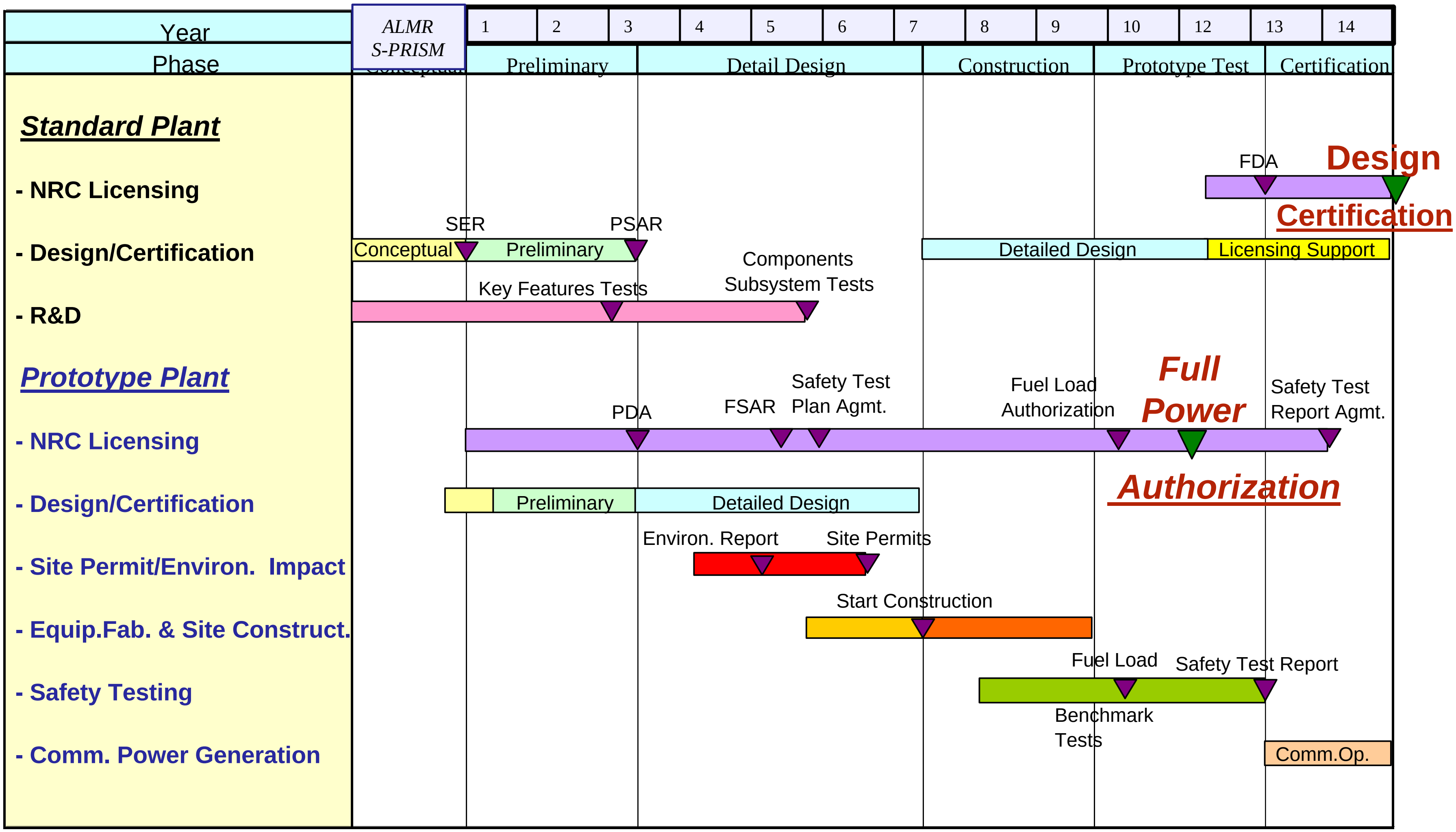
The NRC's Pre-application Safety Evaluation of the ALMR (NUREG-1368) concluded:

"the staff, with the ACRS in agreement, concludes that no obvious impediments to licensing the PRISM (ALMR) design have been identified."

Topics

- Incentive for developing S-PRISM
- Design and safety approach
- Design description and competitive potential
- Previous Licensing interactions
- Planned approach to Licensing S-PRISM
- What , if any, additional initiatives are needed?

Detailed Design, Construction, and Prototype Testing



Design Certification would be obtained through the construction and testing of a single 380 MWe module

Topics

- *Incentive for developing S-PRISM*
- *Design and safety approach*
- *Design description and competitive potential*
- *Previous Licensing interactions*
- *Planned approach to Licensing S-PRISM*
- *What, if any, additional initiatives are needed?*

Safety Review/Key Issues

NAME	LOCATION							
France								
Rapsodie	Cadarache							
Phenix	Marcoule							
SuperPhenix	Creys Malville							
INDIA								
FBTR	Kalpakkam							
ITALY								
PEC	Brasimone							
JAPAN								
Joyo	Oaral							
Monju	Ibarakl							
UK								
DFR	Dounreay							
PFR	Dounreay							
USA								
Clemetine	Los Alamos							
EBR-1	Idaho							
Lampre	Los Alamos							
EBR-2	Idaho							
Enrico Fermi	Michigan							
SEFOR	Arkansas							
FFTF	Richland							
Clinch River	Oak Ridge							
USSR								
BR-2	Obninsk	Research	1956	--	0.1	--	Pu	Hg
BR-5	Obninsk							
BOR-60	Melekess							
BN-350	Shevchenko							
BN-600	Beloyarsk							
BN-800	--							
BN-1600	--							
W. Germany								
KNK	Karlruhe							
SNR-300	Kalkar							
SNR-2	Kalkar	demonstration	--	--	3420	1460	U02/Pu02	Na

Safety Methods

- Containment
- Core energetic potential
- Analysis of Design Basis SG Leaks
- PRA
- Nuclear Methods
- T/H Methods

Fuels

- Validation of fuels data base (metal/oxide)

Waste

- Fission Product Treatment and Disposal

More than 20 Sodium cooled Fast Reactors have been built

Most have operated as expected (EBR-II and FFTF for example)

The next one must be commercially viable

Component Verification and Prototype Testing

Final component performance verification can be performed during a graduated prototype testing program.

Example: The performance of the passive decay heat removal system can be verified prior to start up by using the Electromagnetic Pumps that add a measurable amount of heat to the reactor system

Licensing through the testing of a prototypical reactor module should be an efficient approach to obtaining the data needed for design certification.

Defining the T/H and component tests needed to proceed with the construction and testing of the prototype as well as defining the prototype test program will require considerable interaction with the NRC